SEARCH FOR EXCITED QUARKS IN e^+e^- INTERACTIONS WITH THE CELLO DETECTOR

CELLO Collaboration

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The production of excited quarks has been looked for in e^+e^- interactions at PETRA at center of mass energies up to 46.8 GeV using the CELLO detector. The different final state topologies considered are four-jets, two-jets and two-photons, three-jets, two-jets and one-photon. No deviation from standard QCD predictions is observed, thus yielding limits on the coupling constants and the masses of these possible quark states.

1. Introduction

One of the most direct predictions of composite models is the existence of excited states of quarks and leptons [1,2]. Excited lepton (e^*, μ^*, τ^*) searches have already been reported by CELLO and by other collaborations [3]. In the present analysis we have looked for multi-hadronic events coming from the production and subsequent decay of excited quarks.

In e^+e^- collisions such quarks can be produced either in pairs (due to the normal gauge coupling) or singly (with a tensor coupling at the $qq^*\gamma$ vertex). Excited quarks can return to the ground state electromagnetically by emitting a photon $q^* \to q\gamma$, or strongly by the decay $q^* \to qg$ [‡1].

For single excited quark production we have used an effective interaction lagrangian since the compositeness scale Λ_{comp} is expected to be in the TeV range or above [4]. The effective couplings are deduced from gauge and symmetry properties under the simplifying hypothesis that excited quarks carry the same quantum numbers [‡2] as the normal ones [1,2]:

$$\mathcal{L} = (1/2m_{q^*})\bar{\Psi}_{q^*}[e_q F_{\mu\nu}\sigma^{\mu\nu}(a^\gamma - ib^\gamma\gamma^5) + \tfrac{1}{2}g_s\lambda^j G^j_{\mu\nu}\sigma^{\mu\nu}(a^g - ib^g\gamma^5)]\Psi_q + \text{h.c.}, \qquad (1)$$

where m_{q^*} is the mass of the excited quark, e_q and g_s are the electric and strong charge, and $a^{g,\gamma}$, $b^{g,\gamma}$ are free dimensionless parameters which determine the couplings to gluons and photons, respectively. The rest of the notation follows standard QED and QCD conventions. This lagrangian leads to the decay widths [1]

$$\Gamma_{q^*\to q\gamma} = \tfrac{1}{2}\alpha m_{q^*}\lambda_\gamma^2 \quad \text{and} \quad \Gamma_{q^*\to qg} = \tfrac{2}{3}\alpha_s m_{q^*}\lambda_g^2, \qquad (2)$$

where $\alpha = e_q^2/4\pi$, $\alpha_s = g_s^2/4\pi$, $\lambda_g^2 = |a^g|^2 + |b^g|^2$ and $\lambda_\gamma^2 = |a^\gamma|^2 + |b^\gamma|^2$.

The decay into gluon should dominate if $\lambda_g \approx \lambda_\gamma$. However, the possibility cannot be excluded that unknown dynamics might yield λ_γ larger than λ_g and inhibit the gluon decay. Therefore, our analysis has been performed for the two extreme cases $\Gamma_g \gg \Gamma_\gamma$ (only gluon decay) and $\Gamma_g \ll \Gamma_\gamma$ (only photon decay). Consequently, we have looked for excited quarks in the following processes:

Pair production,

$e^+e^- \to q^*\bar{q}^* \to q\bar{q}gg$ (four-jets),

$e^+e^- \to q^*\bar{q}^* \to q\bar{q}\gamma\gamma$ (two-jets and two-photons).

Single production,

$e^+e^- \to q\bar{q}^*, \bar{q}q^* \to q\bar{q}g$ (three-jets),

$e^+e^- \to q\bar{q}^*, \bar{q}q^* \to q\bar{q}\gamma$ (two-jets and one-photon).

2. Data collection and detector properties

The data used for the present study were collected with the CELLO detector operating at the PETRA

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‡1 Weak decays via virtual Z^0 or $W^\pm$ exchange are also possible but they will not be considered here.

‡2 It could well be that the first excited state is a spin-$\frac{3}{2}$ object (like in the nucleon case); this could lead to cross sections growing faster than the ones considered here [1].

e^+e^- collider. The centre of mass energy varied from 42.5 GeV to 46.8 GeV and the total integrated luminosity was about 34 pb^{-1}.

The CELLO detector has been previously described in detail [5]. The main features of the apparatus used in this analysis are its large and uniform acceptance for charged particles and photons, with a good angular resolution. The detector elements used in the present work are the following ones:

– The central tracking device which measures momenta of charged particles with $|\cos\theta| < 0.9$, where θ is the polar angle between the particles and the positron beam (the z axis). It is made of interleaved drift and proportional chambers in a 1.3 T magnetic field. The resolutions obtained with it in polar angle, azimuthal angle (ϕ), and transverse momentum (p_t) are: $\sigma_\theta = 3$ mrad $\times \sin^2\theta$, $\sigma_\phi = 2$ mrad, and $\sigma(p_t)/p_t = 0.02 p_t$.

– The barrel electromagnetic calorimeter which covers the $|\cos\theta|$ range up to 0.86. It consists of 20 radiation lengths of lead strips immersed in liquid argon. The showers are sampled 7 times in depth and the fine lateral segmentation provides an angular resolution $\sigma_\phi = 6$ mrad in azimuth and $\sigma_\theta = 8$ mrad in θ. Its energy resolution is $\sigma_E/E = 0.05 + 0.10/\sqrt{E}$, where E is the shower energy in GeV.

3. Data selection

The trigger of interest for the present analysis requires at least 2 GeV deposited energy in the barrel liquid-argon calorimeter and at least one charged track in the central detector with a momentum greater than 650 MeV/c transverse to the beam (as determined by a fast hardware processor).

After filtering all the events through the standard CELLO reconstruction programs, the following selection criteria were used to make a multihadronic event preselection:

– charged tracks and neutral showers were accepted if they exceeded 200 MeV/c and 250 MeV, respectively,

– the distance between the interaction point and the track had to be less than 0.4 cm in the transverse view,

– the polar angle of all tracks and showers had to lie in the range $|\cos\theta| < 0.86$,

– to ensure good momenta determination for charged particles, their momentum had to be less than 15 GeV/c,

– total energy $E_t > 0.22\sqrt{s}$,

– more than four charged particles,

– modulus of net charge less than seven.

The number of events which pass these conditions is 6609.

The further cuts used to select specific topologies and optimize the ratio of the signal against the background are described in detail for each case below.

3.1. Pair production. The process leading to $q^*\bar{q}^*$ production by one-photon exchange is the same as for a pair of ordinary quarks. For this case the only unknown quantity in the total cross section is m_{q^*}.

(A) Gluon decay channel. For the reaction $e^+e^- \to q^*\bar{q}^* \to q\bar{q}gg$ we expect an excess in the number of events with four jets where two pairs of them show a similar invariant mass. Therefore we have searched for candidates with:

– charged energy $E_{ch} > 0.22\sqrt{s}$,

– charged tracks in both z hemispheres,

– sphericity and aplanarity greater than 0.5 and 0.06, respectively,

– four and only four jets had to be found by a cluster algorithm [‡3] [6] [‡4].

After all these cuts a kinematical fit was applied to the remaining events. We calculated the four-momenta of the jets using the measured angles and supposing them to originate from massless partons. Then the three possible jet pairing combinations were made and the events were selected only when at least one of these combinations had invariant masses equal within 6 GeV/c^2, in order to satisfy the hypothesis of the production and decay of two identical states. Then we were left with 12 possible candidates while 13 were expected from standard QCD processes.

The detection efficiency for $q^*\bar{q}^*$ after all the requirements mentioned above is around 3.5% as determined from Monte Carlo simulation.

(B) Photon decay channel. For the production of q^*,

[‡3] It reconstructs an arbitrary number of jets using a cluster analysis method based on particle momenta. The distance scale d_{join}, above which two clusters may not be joined, has been chosen to be 3 GeV/c in the four-jet analysis and 1.8 GeV/c in all other cases. Once this algorithm is applied, we reject events which include either a cluster of total energy (charged plus neutral) less than 3 GeV or a cluster whose axis lies outside the $|\cos\theta| < 0.8$ region.

[‡4] We have used the program version known as JETSET5.2.

via $e^+e^- \to q^*\bar{q}^* \to q\bar{q}\gamma\gamma$, we have searched for events with two jets and two hard photons. The selection criteria were the following:

– neutral energy $E_n > 5$ GeV,

– total energy $E_t > 0.4\sqrt{s}$,

– at least one photon with more than 3 GeV and isolated within a cone with an opening angle of 50° from other particles,

– four-jet reconstruction by the cluster algorithm already mentioned,

– two of the four jets must be energy-dominated by one photon each (other particles belonging to the jet should contribute less than 1 GeV).

No events survived these cuts, neither in the data nor in the QCD simulation (even with twice the total luminosity collected), whereas the efficiency for the signal detection is found to be close to 20%.

3.2. Single production. The process giving only one q* is governed by the lagrangian given in eq. (1). It allows to produce excited quarks with $m_q^* \geqslant E_b$. The cross section has now two unknown parameters, m_{q^*} and λ_γ [‡5].

(A) Gluon decay channel. For the reaction $e^+e^- \to (q\bar{q}^*, \bar{q}q^*) \to q\bar{q}g$ the QCD background to the three-jet signature of the q* is very high and consequently it is difficult to see any new effect from the total three-jet hadronic cross section. However, due to the subprocess $q^* \to qg$, two of the jets must have an invariant mass M_{jj} clustering at the q* mass and so one can search for a peak in the invariant mass distributions of our three-jet sample.

We used the same selection criteria as for the pair production process without the last two topology cuts. Afterwards, we applied the cluster algorithm [‡3] optimized for q* topologies. We ask for three and only three clusters and define the event plane by diagonalizing the sphericity tensor. Then the cluster axes are projected onto this plane. To determine the jet momenta from the information of the projected directions of the clusters we require energy–momentum conservation (assuming massless primary partons) and calculate the α, β, and γ parameters in the equations

$$\alpha\bar{p}_1 + \beta\bar{p}_2 + \bar{p}_3 = 0\ ,$$

$$\gamma(E_1 + E_2 + E_3) = \sqrt{s}\ , \quad E_1 \geqslant E_2 \geqslant E_3\ . \tag{3}$$

With the values thus found, we re-scale the four-momenta of the jets. By keeping only those events which have α and β values close to unity, we reject 70% of the events selected by the cluster algorithm.

After these cuts, the three-jet sample contains 480 events. The efficiency for detecting the q* signal is 20% almost independent of the q* mass. The usual QCD background is estimated by Monte Carlo to be around 7% of all the generated events (regardless of the number of partons).

With this method, we achieved a resolution for the two-jet invariant mass of $\sigma(M_{jj}) \simeq 2$ GeV/c^2, almost constant over the whole mass range.

(B) Photon decay channel. In this case we looked for a peak in the photon–jet invariant mass $M_{j\gamma}$ corresponding to the decay $q^* \to q\gamma$ in events with two jets and one energetic photon.

The selection criteria were the same as for the $q\bar{q}\gamma\gamma$ signature except that we demanded only one photon of 3 GeV or more, isolated within a cone with an opening angle of 30°. Then we applied the same three-jet reconstruction algorithm as in the gluon decay case and required that at least half of the photon cluster energy be carried by the photon itself. Finally we obtained 43 candidates.

For this channel the detection efficiency is very

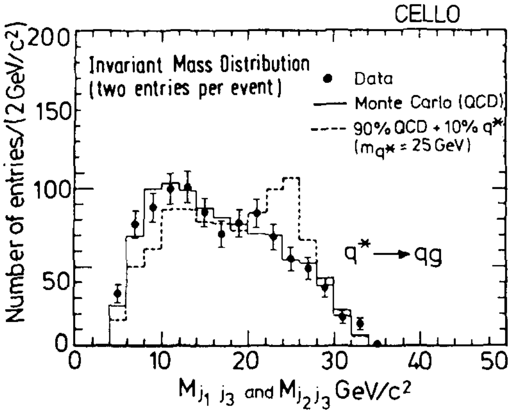

Fig. 1. Jet–jet invariant mass distribution from three-jet events for data and Monte Carlo. The two Monte Carlo distributions (with and without q*) are normalized to the number of events found in data.

[‡5] We have neglected any possible difference between the acceptance of the two q* polarizations introduced by the term $(a g_{\gamma} - i b g_{\gamma}\gamma^5)$.

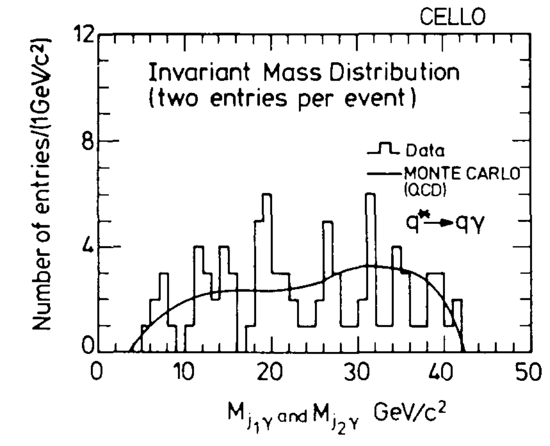

Fig. 2. Jet–photon invariant mass distribution from events with two-jets plus an isolated photon.

similar to the preceding case (20%). Nevertheless the QCD background is much smaller (0.5%).

The resolution at the parton level achieved with this procedure for the jet–photon invariant mass is typically $\sigma(M_{j\gamma}) \simeq 1$ GeV/c^2. This is better than for the gluon channel (jet–jet) because the better direction and energy measurement of the photon and the absence of smearing effects from hadronization.

In both cases the invariant mass distributions (figs. 1 and 2) show good agreement with the QCD expectation alone.

The contamination from two-photon events, tau leptons, QED, cosmics or beam–gas is found to be negligible after Monte Carlo simulation and event scanning.

4. Results and discussion

In the case of pair production the differential cross section reads (assuming no resonance effects)

$$d\sigma/d\Omega = (3\alpha^2 e_q^2/4s)\beta[1 + \cos^2\theta + (1-\beta^2)\sin^2\theta] , \quad (4)$$

where β is the q* velocity.

From the predicted number of events we can derive 95% CL lower limits for the mass of a hypothetical q*. We obtain, for the gluon decay channel 22.3 GeV/c^2 and 21.1 GeV/c^2 depending whether the charge is $\frac{2}{3}$ or $\frac{1}{3}$, respectively. For the photon decay channel we get lower limits of 23.2 GeV/c^2 and 22.5 GeV/c^2 in the corresponding cases.

It should be noticed that with the present analysis we cannot exclude excited quark states below 5 GeV/c^2 because the event topology degenerates into two jets. However, such low masses are already excluded by the total hadronic cross section measurements [7].

To set upper limits on the coupling strength which enters in the lagrangian (1) the following formula is used for the differential cross section of the single q* production [1]:

$$d\sigma/d\Omega = (6\alpha^2 p^*/s^{3/2} m_{q^*}^2)\lambda_\gamma^2 \times [2EE^* + p^{*2}\sin^2\theta - \tfrac{1}{2}(s - m_{q^*}^2)] , \quad (5)$$

where E, E^*, p and p^* are the energies and momenta of the outgoing particles.

From a fit of the standard QCD plus the expected peak for a q* to the shape of the experimental invariant mass distribution, we obtain 95% CL limits for the ratio $(\lambda_\gamma/m_{q^*})^2$ as a function of the q* mass. The results are shown in fig. 3 for e_q set to one.

In our analysis the Monte Carlo simulations for the q* used the string fragmentation scheme for the hadronization of the quarks and gluons [8] and included initial-state radiation. As is well known, the three-jet reconstruction depends on the fragmentation scheme

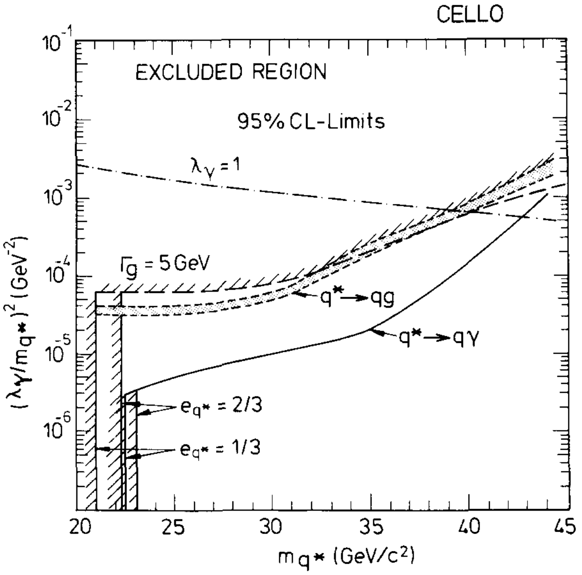

Fig. 3. Limits at 95% CL on $(\lambda_\gamma/m_{q^*})^2$ as function of the excited quark mass. The vertical lines correspond to limits from the pair production which are independent from λ_γ. The dashed lines indicate the limits on λ_γ from single q* production for various values of Γ_g and Λ_{QCD} (see text).

[9]. In particular the Lund fragmentation tends to change the three jets towards the two-jet configuration, thus reducing the reconstruction efficiency and the mass resolution. So it has been used to give safer upper limits.

The QCD background has been evaluated using the Lund Monte Carlo for e^+e^- [6] with second-order corrections and initial- and final-state radiation. We consider the value for the scale parameter Λ_{QCD} = 0.5 GeV and in fig. 3 we show the sensitivity of our limits to Λ_{QCD} in the range 0.1 GeV/$c \leqslant \Lambda_{QCD} \leqslant$ 1.0 GeV/c. The dependence of the limits on the fragmentation parameters (mainly σ_q which determinates the transverse momentum distribution) is much smaller than the one on Λ_{QCD}. Every variation on these parameters has similar effects either on the q* signature and on the QCD background.

Hadrons containing excited quarks are expected [1] if the q* lifetime is long enough ($c\tau_{q^*} \geqslant 1$ fm). This possibility has also been considered and studied but no significant change in the signature and in the upper limits has been found.

Besides we can also take into account the fact that the q* may have a non negligible width Γ. If this is the case ($c\tau_{q^*} \leqslant 1$ fm), propagator effects must be included and the total cross section is given by [1,2]

$$\sigma(s, m_{0q^*}) = \frac{1}{\pi} \int_{m_q^2}^{(\sqrt{s}-m_q)^2} dm_{q^*}^2 \frac{m_{q^*}\Gamma}{(m_{q^*}^2 - m_{0q^*}^2)^2 + m_{q^*}^2\Gamma^2} \times \sigma(s, m_{q^*}) . \quad (6)$$

This has the effect of deteriorating the signal in the invariant mass distribution as it makes the peak broader though it extends the sensitivity near the center of mass energy. We have computed this possibility for an extreme case of Γ_g = 5 GeV corresponding to $\lambda_g \approx 1$ (see eq. (2)). The difference on the limits obtained is shown in fig. 3. As far as the photon decay channel is concerned, the experimental limits on λ_γ constrain the decay width Γ_γ to be small. Thus these propagator effects can be neglected.

The limits obtained for the photon decay channel are of the same order as those of the μ^* and the τ^* [3]. This is principally due to the color factor which increases the statistics, thus compensating for the poorer resolution.

5. *Conclusion*

We have searched for excited quarks in the following topologies: four-jets, two-jets and two-photons, three-jets, two-jets and one-photon. We observe good agreement of our data with the known QCD processes up to the highest PETRA energy of 46.8 GeV.

Assuming the excited quark to decay via gluon emission, we conclude that at the 95% CL no excited quark exists below 21.1 GeV/c^2 for a quark charge $\frac{1}{3}$. In the photon decay channel case we exclude them below 22.5 GeV/c^2. For a quark charge of $\frac{2}{3}$ these limits become 22.3 GeV/c^2 and 23.2 GeV/c^2, respectively.

Limits are also put for both q* decay channels on the q*qγ coupling strength, up to q* masses of about 40 GeV/c^2.

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