A MEASUREMENT OF THE TOTAL CROSS SECTION AND A STUDY OF INCLUSIVE MUON PRODUCTION FOR THE PROCESS $e^+e^- \to$ HADRONS IN THE ENERGY RANGE BETWEEN 39.79 GeV AND 46.78 GeV

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The total cross section and the inclusive muon cross section for the process $e^+e^- \to$ hadrons have been measured in the center of mass energy range between 39.79 and 46.78 GeV. The ratio R shows no significant structure. It has an average value of $4.13 \pm 0.08 \pm 0.14$. An upper limit is set on the production of narrow resonances. Limits are obtained for pair-produced heavy quarks. The data are compared with the standard electroweak interaction model including QCD corrections taking into account the five known types of quarks. Upper limits are given for a possible structure of quarks and for effects of color octet leptons.

Introduction

Recently PETRA reached its highest energy of 46.78 GeV. A fine energy scan was performed in the centre of mass (CM) energy range between 39.79 and 46.78 GeV with steps of 30 MeV corresponding to the PETRA energy spread at these energies. An integrated luminosity of about 60 nb^{-1} was accumulated at each energy. The total integrated luminosity was 14.2 pb^{-1} yielding 3031 detected multihadronic events. The total cross section for hadron production was measured and a search was made for narrow resonances with particular reference to toponium, the bound state of the charge $\frac{2}{3}$ top quark. Should toponium be encountered, it is expected to enhance the total cross section by a factor of 2–3 depending on the magnitude of the electronic decay width, Γ_{ee}, and the hadronic branching ratio, B_{had}, which varies with the QCD coupling constant α_s.

If the $t\bar{t}$ ground state were located in the energy range 36.72–39.79 GeV which was not covered completely by PETRA, a step in the total hadronic cross section due to continuum production of top quarks would be expected. The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{pt}$ with σ_{pt} being the total cross section for pointlike fermion pair production should increase by $\Delta R = \frac{4}{3}$. Due to weak decays of t-mesons, an increase of the inclusive muon production in the hadronic events should also occur. In the absence of any thresholds for new particle production the total cross section can be compared to the predictions of the standard model of electroweak interactions and QCD.

In the following we report on an investigation of these topics. It is a continuation of our previous work on searches for narrow resonances [1], on a precise determination of R [2] and on inclusive muon production [3] performed at lower energies. The trigger conditions, the event selection criteria, the determination of the acceptance as well as the corrections and the systematic errors are extensively discussed in ref. [2]. Details on the JADE detector and on the selection of inclusive muons are found elsewhere [2,4,5]. Thus we confine this paper to the presentation of the results.

R-values

The R-values are shown in fig. 1 as a function of the CM energy. The overall normalization error is estimated to be 3.3% apart from the contribution from radiative corrections of order α^4 or higher. The point-to-point error for the scan data is ±1%. The data are consistent with a constant value of R in the scanned energy range. The average value $\langle R \rangle = 4.13 \pm 0.08 \pm 0.14$, where the second error is the overall normalization error, is in good agreement with other measurements [6,7] obtained in the same energy range. It is

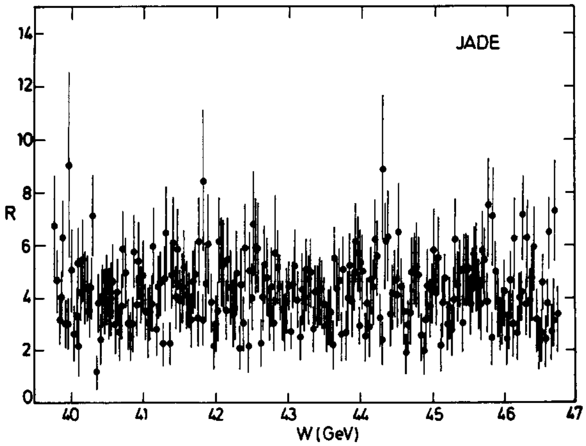

Fig. 1. The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{pt}$ measured between W = 39.79 GeV and 46.78 GeV with steps of 30 MeV.

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consistent with the R-value measured at 34.6 GeV, $\langle R\rangle = 3.97 \pm 0.05 \pm 0.10$ [2], although it tends to show a slight increase with the energy, as expected in the standard model.

Narrow resonance search

The possible existence of a narrow $q\bar{q}$ vector resonance is investigated by fitting the data to a constant R-value plus a narrow resonance peak. The largest resonance signal is observed at a mass of 42.56 GeV/c^2. Since this signal is not statistically significant, a 95% confidence level (CL) upper limit on the integrated cross section of a narrow state can be determined:

$$\int \sigma_{\mathrm{v}} \cdot \mathrm{d}W < 23.7 \text{ nb MeV} \quad \text{or} \quad \Gamma_{\mathrm{ee}} B_{\mathrm{had}} < 1.9 \text{ keV},$$

where $W = \sqrt{s}$ is the CM energy, Γ_{ee} is the electronic decay width and B_{had} is the hadronic decay branching ratio of the $q\bar{q}$ resonance. In obtaining the limit, the observed number of events is compared to the expected one at each energy point taking radiative corrections [8], which reduce the resonance height by about a factor two, and the PETRA energy spread, $\sigma \sim 41$ MeV at 44 GeV, into account. This limit excludes the existence of the lowest mass $t\bar{t}$ state, which is expected to have $\Gamma_{\mathrm{ee}} B_{\mathrm{had}} \sim 4$ keV, in the scanned energy range. A charge $-\frac{1}{3}$ quark bound state, however, is not ruled out. It should be mentioned that this conclusion is based on the assumption that the detection efficiency for the toponium hadronic decay is not lower than that of the nonresonant hadronic final states for our selection criteria. According to Monte Carlo simulations in the framework of the standard model this assumption is justified.

A similar analysis can be made for a postulated narrow scalar resonance X which was suggested in order to explain the radiative Z^0 decays, $Z^0 \to e^+e^-\gamma/\mu^+\mu^-\gamma$ observed at the $\bar{p}p$ collider [9]. A possible composite-model explanation of such decays is that the Z^0 firstly decays radiatively into its scalar partner X which then decays into a lepton pair [10–12]. The observed events suggest that the X scalar would have a mass in the range 40–50 GeV/$c^2$2. Should such a particle exist, it would contribute to R through the interaction

$$e^+e^- \to X \to q\bar{q} \to \text{hadrons}. \tag{1}$$

The corresponding increase in R is

$$\Delta R(s) = \epsilon \frac{3s^2}{\alpha^2 M_X^2} \frac{\Gamma_{X\to ee} \cdot \Gamma_{X\to had}}{(s - M_X^2)^2 + M_X^2 \Gamma_X^2}, \tag{2}$$

where α is the fine structure constant, M_X is the mass of X, Γ_X is the total width of X and $\Gamma_{X\to ee}$ and $\Gamma_{X\to had}$ are the partial decay widths of X into an electron pair and hadrons, respectively. The parameter ϵ is equal to 1 if X is a singlet or 2 if it is a doublet. For a narrow scalar/pseudoscalar X, the same analysis as in the case of a $q\bar{q}$ vector resonance can be applied taking radiative corrections and the beam energy spread into account. In fact the detection efficiency for $X \to q\bar{q}$ is slightly larger than that for quarkonium, but we neglect the difference. Eq. (2) gives an upper limit of

$$\epsilon\, \Gamma_{X\to ee} \Gamma_{X\to had} / \Gamma_X < 6.0 \text{ keV} \quad (95\%\ \text{CL}), \tag{3}$$

for a narrow X with $\Gamma_X < 10$ MeV. If quark–lepton universality holds for the coupling to X, namely, $\Gamma_{X\to had} = n\Gamma_{X\to ee}$, with n being the number of contributing quarks, $n = 15$, the limit can be rewritten as

$$\sqrt{\epsilon}\, \Gamma_{X\to ee} < 0.63 \sqrt{\Gamma_X} \text{ keV} \quad (\Gamma_X \text{ in keV}). \tag{4}$$

This limit can be compared with the lower limit deduced from the collider data [12],

$$\epsilon \Gamma_{X\to ee} > 2 \text{ MeV}. \tag{5}$$

The existence of a narrow X with a large $\Gamma_{X\to ee}$ is thus excluded in the scanned region. Similar analyses have been reported by other experiments [13,6].

Heavy quark production

Step in R. Limits for the pair production cross section of new flavour quarks can be obtained from the data by assuming their contribution to the R-value to be a step function positioned at the production threshold energy. This seems to be more realistic than assuma point-like behaviour $\beta(3 - \beta^2)/2$ (β being the velocity of the particle) of a spin-$\frac{1}{2}$ particle if QCD effects are taken into account [14]. The R-values are averaged over two energy ranges, $W < W_{\mathrm{th}}$ and $W > W_{\mathrm{th}}$, where W_{th} is the hypothetical threshold energy for the new flavour production. Upper limits of the height of the step are calculated as a function of W_{th}. For this analysis our low energy data between 12 GeV and 36.38 GeV [2] are included. If the same acceptance is assumed for the new flavour hadronic final states, the expected step in R is $\frac{4}{3}$ ($\frac{1}{3}$) for a charge $\frac{2}{3}$ ($-\frac{1}{3}$) quark.

We exclude the pair production of a new charge $\frac{2}{3}$ quark in the energy range $W_{th} < 46.6$ GeV at the 95% CL. Similar analyses are reported by TASSO [7] and MARK-J [15]. For a charge $-\frac{1}{3}$ quark the pair production is excluded only at the 90% CL in the energy range $W_{th} < 43.78$ GeV.

Inclusive muons. A further independent method of searching for heavy quarks involves the analysis of muon-inclusive multihadron events. A heavy quark is expected to have a semi-leptonic branching ratio similar to that of the b quark. Consequently an increase in muon yield would be observed once the top pair threshold is crossed. Fig. 2 shows the yield of inclusive muons in the hadronic events in the scanned energy range. The muon tracks were required to have a minimum momentum of 1.8 GeV/c. Above this value the prompt muon detection efficiency is approximately 65% for events below a new quark threshold. Due to background the fraction of prompt muons in the muon inclusive sample is about 35%. No significant increase in muon production is evident.

In addition a large fraction of muons resulting directly from the weak decay of a heavy quark will be produced with large transverse momenta, p_T, relative to the jet axis. The event shape will be more spherical for an event initiated by a heavy quark. The muon p_T distribution and the observed event shape parameters, such as thrust, aplanarity and jet mass, M_{jet}, are consistent with Monte Carlo predictions including five quarks. Using an event selection designed to isolate heavy quarks, a quantitative limit can be derived on the semi muonic branching ratio of the new quark. The applied cuts were

$$p_T(\mu) > 1.6\ \mathrm{GeV}/c,$$

$$M_{jet} = \frac{\sqrt{s}}{E_{vis}} \sum |p_T^{out}| > 12\ \mathrm{GeV}/c^2, \qquad (6)$$

where p_T is measured with respect to the thrust axis; the sum runs over all charged particles and photons and E_{vis} is the total visible energy of the event; $|p_T^{out}|$ is the transverse momentum out of the event plane which is defined by the momentum tensor analysis. One event passed these cuts, giving a limit of Br(t(b′) → μ) as shown in fig. 3, as a function of the mass of a new quark. Comparing this limit with the expected muonic branching ratio for a heavy quark, of about 10% as indicated in fig. 3, the existence of a charge $\frac{2}{3}$ quark is excluded up to a mass of 23 GeV/c^2. A similar analysis for a charge $-\frac{1}{3}$ quark including the old data at 34.2 GeV (for which a less stringent jet mass cut was used) rules out a mass between 6 GeV/c^2 and 22 GeV/c^2 at the 95% CL.

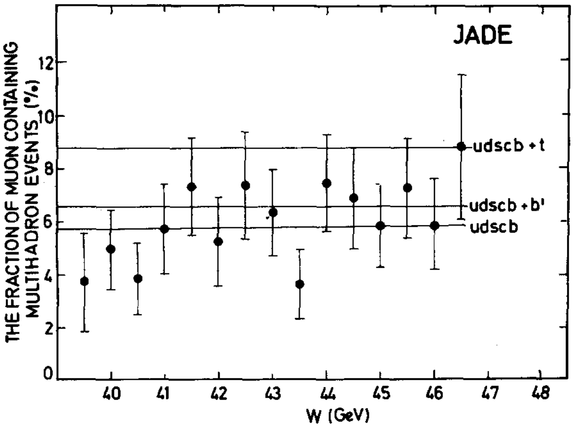

Fig. 2. The fraction of inclusive muon events for different beam energies.

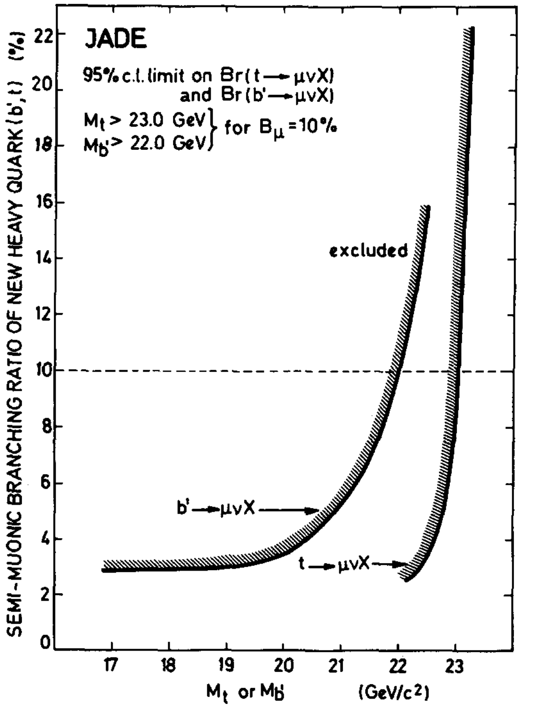

Fig. 3. Limits on the semi-muonic decay branching ratios for charge $\frac{2}{3}$ and $\frac{1}{3}$ heavy quarks.

Combining results of the R-value analysis and the inclusive muon analysis, the production of a heavy quark of charge $\frac{2}{3}$ is excluded for a mass up to 23.3 GeV/c^2 and the production of a heavy quark of charge $-\frac{1}{3}$ which has the semi-muonic branching ratio of 10% is excluded between 6 GeV/c^2 and 22 GeV/c^2.

Fit to the standard electroweak interaction model

The present R-values and the previous data [2] were combined and fitted to the standard electroweak interaction model with QCD corrections [14]. The free parameters in the fit were the QCD scale parameter Λ_s, the electroweak mixing angle $\sin^2\vartheta_W$ and the overall normalization factor f. The scan data were averaged over bins of 1 GeV center of mass energy. Using the same procedure as described in ref. [2], which takes first order QCD corrections into account, the fit gives

$$\alpha_s(30\ \mathrm{GeV}) = 0.20^{+0.06}_{-0.07}, \quad \sin^2\vartheta_W = 0.23^{+0.03}_{-0.04},$$

$$f = 0.99 \pm 0.02, \qquad (7)$$

with $\chi^2 = 11.2$ for 17 degrees of freedom. The errors include both statistical and systematic errors. The curve fitted with these parameters is shown in fig. 4 together with the data. The new results are in good agreement with our previous values [2,16] and with those obtained by other experiments [17,18,7]. In our previous analysis, a solution at $\sin^2\vartheta_W = 0.55$ also existed. This, however, is removed by the present high energy measurement. The obtained $\sin^2\vartheta_W$ implies the mass of Z^0 is (88.6 + 6.4/−3.6) GeV/c^2 in agreement with the $\bar{p}p$ collider data [9].

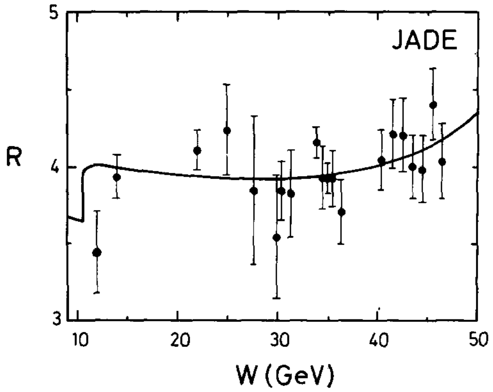

Fig. 4. The ratio R averaged in bins of 1 GeV CM energy combined with our previously published data [2]. The curve represents the best fit to the standard electroweak interaction model with QCD corrections with $\alpha_s(30\ \mathrm{GeV}) = 0.20$ and $\sin^2\vartheta_W = 0.23$.

Pointlike nature of quarks

The pointlike nature of quarks can be examined by fitting the R-values with a form factor $F(s)$,

$$R_{obs}(s) = R(s)|F(s)|^2, \quad F(s) = 1 \pm s/(s - \Lambda_\mp^2), \qquad (8,9)$$

with $\Lambda_\mp$ as free parameters. For $R(s)$, the same expression as for the analysis described in the preceding section was used with the parameters set at $\sin^2\vartheta_W = 0.228$ and $\alpha_s(30\ \mathrm{GeV}) = 0.18$. The overall normalization was adjusted within the error in order to calculate the limits of the Λ. The fit gave $\Lambda_+ > 277$ GeV and $\Lambda_- > 266$ GeV at the 95% CL. Similar results have been reported by TASSO [18].

Mass limit of a colored electron

Some composite models predict the existence of colored leptons, L_8, which form a color octet [19]. They couple to the ordinary leptons and gluons by the interaction

$$\mathcal{L} = (\lambda/2M)\,\bar{L}_8^c G_{\mu\nu}^c \sigma^{\mu\nu} L + \mathrm{h.c.}, \qquad (10)$$

where c runs over the octet of vector gluons, λ is the strength of the LL_8g coupling and is expected to be O(1) and M is the mass of the L_8 [20]. Should color octet electrons, e_8, exist, e^+e^- could then annihilate into two gluons by the exchange of an e_8. The cross section of the reaction, $e^+e^- \to gg$, is given by a formula similar to that for the reaction, $e^+e^- \to \gamma\gamma$, via the exchange of an excited electron [21]. For a heavy e_8 the cross section is written as

$$\sigma = (8/\pi)\,\lambda^4 s^2/M^6, \qquad (11)$$

where the factor 8 is due to the octet of gluons. An increase in the R-value due to this reaction has a strong s-dependence which is not observed in fig. 4. A fit to the R-values including eq. (11) gives an upper limit for λ^4/M^6 to be 3.76×10^{-14} (GeV^{-6}) (95% CL). Thus a limit on the mass of e_8 is obtained:

$$M > 173\,\lambda^{2/3}\ (\mathrm{GeV}).$$

Conclusions

R-values and the inclusive muon cross sections have been measured in the CM energy range between 39.79

and 46.78 GeV. The R-values are flat in this range with an average value of 4.13 ± 0.08 ± 0.14, excluding the existence of a narrow resonance. For a vector quarkonium, a limit $\Gamma_{ee}B_{had} < 1.9$ keV was obtained at 95% CL. For a spin zero narrow resonance X, a 95% CL limit was put at $\epsilon\Gamma_{X\to ee}B_{had} < 6.0$ keV. Assuming lepton–quark universality, this limit is inconsistent with a lower limit for $\Gamma_{X\to ee}$ estimated to explain the radiative Z^0 decay in a composite scheme. The muon inclusive cross section can be well accounted for in the standard electroweak model including five quark flavours. Combining the R-data and the muon inclusive cross sections, a new quark with charge $\frac{2}{3}$ is ruled out for masses below 23.3 GeV/c^2 at 95% CL. For a charge $-\frac{1}{3}$ quark, the mass range between 6 and 22 GeV/c^2 is excluded. A fit to the standard electroweak interaction model yields α_s(30 GeV) = 0.20 + 0.06/−0.07 and $\sin^2\vartheta_w$ = 0.23 + 0.03/−0.04. For an examination of the pointlike nature of quarks, the data set 95% CL lower limits on the cutoff parameters of the quark form factors to be $\Lambda_+ > 277$ GeV and $\Lambda_- > 266$ GeV. For color octet electrons, a limit on the mass and the ee_8g-coupling constant is found to be $M > 173\ \lambda^{2/3}$ GeV/c^2.

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