MEASUREMENT OF R AND SEARCH FOR THE TOP QUARK IN e^+e^- ANNIHILATION BETWEEN 39.8 AND 45.2 GeV

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Received 13 January 1984

e^+e^- annihilation into hadrons was studied at CM energies between 39.8 and 45.2 GeV and a search was made for new heavy quarks. No evidence was found for the existence of a narrow state excluding the possible existence of the lowest vector toponium state in this mass range. A search for continuum production of heavy quarks led to lower mass limits for new quarks of 22.0 GeV ($e_Q = 2/3$) and 21.0 GeV ($e_Q = 1/3$). Quarks are found to be pointlike, the corresponding mass parameter being larger than 288 GeV. A fit of the QCD and the electroweak contributions to $R = \sigma_{tot}/\sigma_{\mu\mu}$ yielded $\sin^2\theta_W = 0.30^{+0.23}_{-0.07}$.

Electron–positron annihilation provides a straightforward test of the existence of new heavy quarks Q. They will show up as narrow vector bound states $(Q\bar{Q})$ leading to enhancements in the ratio $R = \sigma_{tot}/\sigma_{\mu\mu}$ of the total hadronic cross section to the μ pair cross section ($\sigma_{\mu\mu} = 4\pi\alpha^2/3s$). Some 2 GeV above the lowest vector state $Q\bar{Q}$ continuum production is expected which, ignoring threshold factors, leads to an increase in R of $\Delta R = 3e_Q^2$ (e_Q = quark charge) and to the appearance of "spherically" shaped events which are easily discernible from the dominant two-jet events. Previous searches conducted at PETRA up to CM energies W of 43 GeV have excluded the existence of the top quark ($e_Q = 2/3$) for a mass below 20.3 GeV where M_Q is defined with respect to the threshold for continuum $Q\bar{Q}$ production, $W_{thresh} = 2M_Q$ [1–5] [‡1]. These measurements have also ruled out the existence of an $e_Q = 1/3$ quark for $7 < M_Q < 19$ GeV [4–6].

In this letter we report on a search for heavy quarks up to CM energies of $W = 45.2$ GeV, the highest energy so far reached in e^+e^- storage rings. In addition to the information on heavy quarks the data on R allow a measurement of the electroweak interference contribution and of the weak mixing angle θ_W.

The experiment was performed at the DESY e^+e^- storage ring PETRA with the TASSO detector. An energy scan was performed in steps of $\Delta W = 0.030$ GeV between $W = 39.8$ and 45.2 GeV, collecting at each step an integrated luminosity of $\sim 60\ \mathrm{nb}^{-1}$ which would yield ~ 10 accepted multihadron events given an R value of 4.

The measurements were done with an upgraded TASSO detector. A small high precision cylindrical drift chamber called the vertex detector was installed in summer of 1982 inside the existing tracking chambers. Compared to our previous setup the new thin beam pipe of 1.8 mm beryllium (0.6% rl) significantly reduced the amount of nuclear interactions and photon conversions in front of the first track detection and improved the cleanliness of the multihadron events. Since, however, the tracking information from the vertex detector is not essential for and has not been included in the present work, we postpone a description of it until a future publication.

A new forward detector was installed in spring 1982. It consists of two identical modules each of which has a trigger hodoscope of scintillation counters, three layers of proportional tube chambers and a lead scintillator sandwich shower counter with a thickness of 21 rl covering scattering angles between 28 and 118 mrad. For luminosity measurements there is an additional system of four pairs of precisely aligned scintillation counters. The luminosity is measured via small angle Bhabha scattering in 8 identical arms each consisting of an acceptance defining counter (42–54 mrad) and a somewhat larger counter on the opposite side of the interaction point, both being covered by the corresponding shower counters. The setup is similar to that of ref. [7].

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[13] Supported by the Minerva Gesellschaft für Forschung mbH.
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[‡1] For a review of previous data see ref. [6].

The data taking, analysis procedure and event selection have been described in ref. [3]. The $e^+e^- \to$ multihadron events were detected in the central detector using the information on charged particles. In distinction to ref. [3] the trigger required at least 5 charged tracks with polar angles $|\cos\theta| < 0.8$ and minimum momenta perpendicular to the beam of $p_{xy} > 0.32$ GeV/c.

A total of 1871 events passed the acceptance criteria. To compute the value of R corrections had to be made for beam gas and beam pipe scattering [$(1.5 \pm 0.7)\%$], $\gamma\gamma$ processes [$(1.0 \pm 0.5)\%$] and τ pair production [$(0.5 \pm 0.4)\%$]. The contamination by events from Bhabha scattering was found to be negligible. The systematic uncertainty of the corrected number of events was estimated to be 1.0%.

The luminosity L was determined independently from small angle Bhabha scattering in the forward detector and from wide angle Bhabha scattering in the central detector. The systematic errors for the first and second measurements were estimated to be 3.4% and 5.3%, respectively. The two measurements agreed to better than 3%. The two measurements were averaged and gave a total integrated luminosity of 10.2 pb^{-1}. The systematic error was estimated to be 2.9%.

The value of R at a given CM energy W was determined from the number of accepted events, N_{meas}, the number of background events, N_{bg}, the luminosity L and the acceptance A by

$$R = (L\sigma_{\mu\mu})^{-1}(N_{\text{meas}} - N_{\text{bg}})/A .$$

The acceptance A includes radiative effects [8]. It is computed by weighting with the spectrum of photons radiated in the initial state (for details see ref. [3]). The acceptance was calculated generating Monte Carlo events [9,10] according to $e^+e^- \to q\bar{q}, q\bar{q}g$ using independent jet [11] and string fragmentation [10], respectively, and employing two independent programs to simulate the detector response. The fragmentation parameters used have been determined in a previous α_s analysis [12]. The generated events were followed through the detector and passed through the track reconstruction and acceptance programs used for the real data. The two simulation programs were found to give the same acceptance to within 4%. For the evaluation of R the two results were averaged leading to a systematic uncertainty of 3%.

Adding in quadrature the systematic errors given above plus a 2.5% error to account for uncertainties in the radiative corrections, particularly for the higher order effects which have been neglected, the total systematic error is 4.9%. It represents an overall normalization uncertainty. The systematic point-to-point error for the data in the scan between 39.8 and 45.2 GeV is estimated to be less than 2%.

Narrow states. Fig. 1a presents the R values in steps of $\Delta W = 0.30$ GeV as measured in the scan between 39.8 and 45.2 GeV. Only statistical errors are given. The CM energy spread produced by quantum fluctuations of the beams is $\sigma_W = \pm 0.040$ GeV at $W = 42.5$ GeV and rises proportional to W^2. No statistically significant structure in R is observed. The data are consistent with a constant R. Proceeding as in ref. [1] an upper limit on the cross section contribution of a narrow ($\Gamma < 10$ MeV) state of

$$\int \sigma \, dW < 30.0 \text{ nb MeV} \quad (95\% \text{ CL}) ,$$

was obtained. This limits the product of the leptonic width Γ_{ee} and the hadronic branching ratio B_h for a narrow vector state to

$$\Gamma_{ee} \cdot B_h < 2.4 \text{ keV} \quad (95\% \text{ CL}) .$$

It excludes with 3.1 SD the presence of the lowest energy vector bound state $Q\bar{Q}$ for charge 2/3 quarks for which $\Gamma_{ee} \sim 5$ keV and $B_h \sim 0.7$ is expected [13], while a charge 1/3 $Q\bar{Q}$ state cannot be ruled out ($\Gamma_{ee} \simeq 1.3$ keV, $B_h \simeq 0.7$).

Heavy quark continuum production. An average of the scan data over wider W intervals yielded the following R values, $R = 4.08 \pm 0.12 \pm 0.20$ ($W = 39.8$–43.1 GeV) and $R = 4.22 \pm 0.16 \pm 0.21$ ($W = 43.2$–45.2 GeV). These R values are shown in fig. 1b together with lower energy data from this and other experiments [‡2]. There is no evidence for a step in R between 14 and 45.2 GeV.

In the quark–parton model pair production of heavy quarks in the continuum contributes $R_Q = 3e_Q^2 \times \beta(3 - \beta^2)/2$ where β is the quark velocity, $\beta^2 = 1 - 4M_Q^2/W^2$. QCD effects are expected to increase the contribution near threshold [14] so that the asymptotic expression $R_Q = 3e_Q^2$ may give a better estimate. For a top quark the asymptotic contribution is 4/3 raising R to a value above 5. No such increase is seen in the data.

[‡2] Cited in ref. [5].

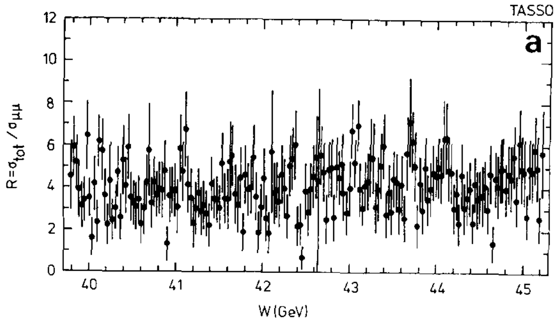
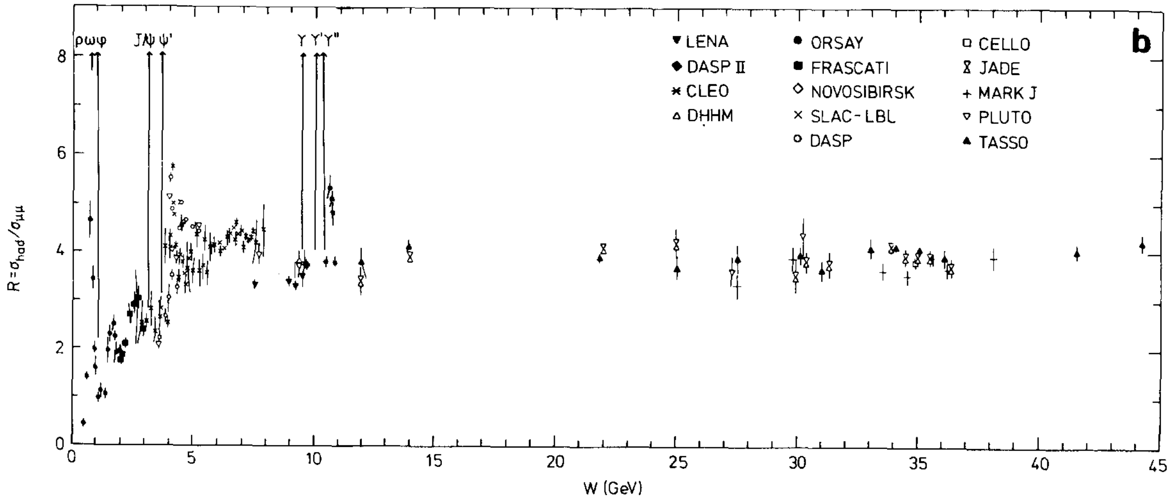


Fig. 1. (a) The ratio $R = \sigma_{tot}/\sigma_{\mu\mu}$ measured in the scanning mode between 39.8 and 45.2 GeV. (b) The ratio $R = \sigma_{tot}/\sigma_{\mu\mu}$ as measured by this and other experiments (cited in ref. [5]). Only statistical errors are shown.



In order to derive a lower limit W_{th} for the $t\bar{t}$ threshold from our data we adopted the following procedure. Various W regions $W_{th} < W < W_{max}$ were considered where W_{th} increases in steps of 0.4 GeV from 39.8 to 45 GeV and $W_{max} = 45.2$ GeV is the maximum CM energy achieved in this experiment. For each W region the average R, called $R(W_{th}, W_{max})$ was determined. The data points in fig. 2a show the measured $R(W_{th}, W_{max})$ values as a function of W_{th}. Fig. 2a also shows the average R for the region $14 < W < 38$ GeV (full line) and the R expected for $W_{th} < W < W_{max}$ assuming that W_{th} is equal to the $t\bar{t}$ threshold.

The expected R values were derived for the two possibilities of the $t\bar{t}$ contribution considered above: (a) it is given by the asymptotic value; (b) it is modified by the threshold factor. From the expected R value and the luminosity collected in a given (W_{th}, W_{max}) interval the expected number of events and its statistical uncertainty were calculated. The shaded bands shown in fig. 2a show the predictions for $R(W_{th}, W_{max})$ calculated under the assumptions (a) and (b), respectively. The upper curve of each band represents the predicted value, the lower line represents the 95% confidence lower limit. We find that a $t\bar{t}$ threshold below 44.8 GeV for assumption (a) and below 42.4 GeV for assumption (b) is excluded at 95% confidence, leadint to lower limits for the quark masses of 22.4 GeV and 21.2 GeV, respectively.

The sensitivity to heavy quark production can be greatly improved by considering also event shapes. Event shapes were studied in terms of sphericity (S) and aplanarity (A) which are defined by $S = \frac{3}{2}(1 - Q_3)$ and $A = \frac{3}{2} Q_1$, where Q_1 and Q_3 are respectively, the smallest and largest normalized eigenvalues of the momentum tensor [15]

$$M_{\alpha\beta} = \sum_{j=1}^{N} P_{i\alpha} P_{\beta}$$

($\alpha, \beta = x, y, z$) for all N charged tracks.

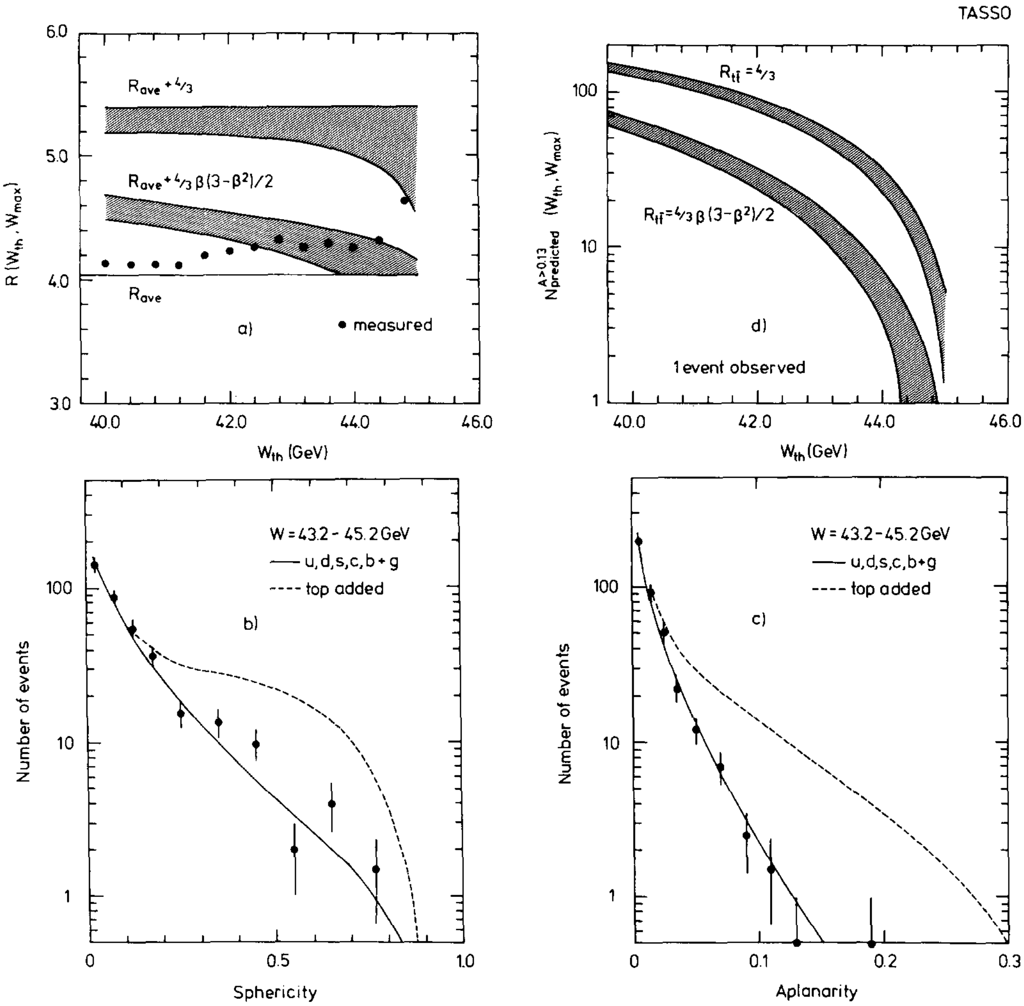


Fig. 2. (a) The ratio $R = \sigma_{tot}/\sigma_{\mu\mu}$ averaged over the interval $W_{th} < W < W_{max}$ as a function of W_{th}. Note, the measured data are shown without error bars. The shaded bands show the predictions if a $t\bar{t}$ contribution is included. The upper curve of each band shows the predicted value, the lower curve shows the 95% confidence lower limit. (b) The observed (uncorrected) sphericity distribution for CM energies between 43.1 and 45.2 GeV. The solid curve shows the QCD prediction for the five known quarks. The dashed curve shows the prediction if a $t\bar{t}$ contribution of $R_{t\bar{t}} = 4/3$ is included assuming a top mass of 20 eGV. (c) The observed (uncorrected) aplanarity distribution. The curves have the same meaning as in fig. 2b. (d) The number of events with aplanarity $A > 0.13$ in the interval (W_{th}, W_{max}). The shaded bands show the expectation for the $t\bar{t}$ contribution evaluated for the two different assumptions given in the text. The upper curve for each shaded band shows the predicted value, the lower curve shows the 95% confidence lower limit.

The sphericity measures the degree of collimation of the final state particles into two jets while aplanarity represents the deviation from a planar event shape. Pair production of the five quarks u, d, s, c, b leads to collinear events ($S \sim 0, A \sim 0$), single hard wide angle gluon emission produces non-collinear planar events ($S > 0, A \sim 0$) while pair production of a heavy quark near threshold results predominantly in noncollinear nonplanar events.

For the following analysis events with hard photon production in the initial state were suppressed by requiring $|\cos\theta_n| > 0.2$ where θ_n is the angle between the normal to the event plane and the beam direction. To ensure large acceptance for particles, only events were considered with $|\cos\theta_s| < 0.7$ where θ_s is the angle between the sphericity axis and the beam direction. Figs. 2b, 2c show the observed (i.e. uncorrected) distributions of S and A for all data from $W = 43.2$ to 45.2 GeV. The solid curves show the prediction of a QCD string model [10,12] summing over the five known quarks and including second order terms in α_s. (QED radiative effects and detector effects were taken into account). They represent the data well. The dashed–dotted curves show the QCD prediction if a top mass of $M_Q = 20$ GeV is assumed and a top quark contribution of $R_{t\bar{t}} = 4/3$ is added. The $t\bar{t}$ final states were treated as in ref. [16]. The data show no evidence for such a $t\bar{t}$ contribution.

A similar analysis as above was performed to determine a lower limit for a possible $t\bar{t}$ threshold from the aplanarity distribution. Fig. 2d presents the predicted number of events with $A > 0.13$ in the interval (W_{th}, W_{max}) which should be observed if $t\bar{t}$ production is present. The two bands show the predictions according to assumptions (a) and (b), respectively, and ignoring possible contributions from the known five quarks. The upper curve of each band represents the predicted value, the lower line the 95% confidence lower limit. The predictions have to be compared with the one event observed between 43.2 and 45.2 GeV. We conclude from fig. 2d that a $t\bar{t}$ threshold below 44.8 GeV for assumption (a) and below 44.0 GeV for assumption (b) is excluded at 95% confidence leading to lower limits for the quark masses of 22.4 GeV and 22.0 GeV, respectively. The data presented in fig. 2d can also be used to set limits on the threshold of a possible charge 1/3 quark. Under the assumption that the topology of the hadronic final states is similar to that expected for $t\bar{t}$ production the expected contribution is a factor of four smaller than for t quarks. We find the following lower mass limits for $e_Q = 1/3$ quarks at 95% confidence: 22.0 GeV for assumption (a) and 21.0 GeV for assumption (b).

Quark structure. The high-energy data on R can be used to test whether quarks are point-like, provided the quark–parton picture is correct. In terms of the quark magnetic form factor G_M, R is given by [17]

$$R/R_0 = |G_M(s)|^2 ,$$

with the ansatz $G_M(s) = (1 - s/M^2)^{-1}$. Treating R_0 as a free parameter and correcting for the weak contribution (using the standard theory and $\sin^2\theta_W = 0.229$, see below) the data for $W \geqslant 14$ GeV yield $M > 288$ GeV (95% CL). If quarks are composites of three subquarks G_M may have a dipole behaviour, $G_M = (1 - s/M_D^2)^{-2}$. For this case the fit gives $M_D > 408$ GeV (95% CL). The result can also be expressed in terms of the cut-off parameters, $G_M(s) = 1 \mp s/(s - \Lambda_\pm^2)$ which yields $\Lambda_+ = M > 288$ GeV and $\Lambda_- > 372$ GeV.

Comparison with weak contributions. The second order QCD prediction for R is given by [18]

$$R = 3 \sum e_q^2 [1 + \alpha_s/\pi + C_2(\alpha_s/\pi)^2] ,$$

where $C_2 = 1.39$ in the $\overline{\rm MS}$ scheme. We used for the strong coupling $\alpha_s = 0.17$ at $W = 34.5$ GeV. The energy dependence of α_s was described in terms of the QCD parameter Λ using the second order formula [18].

The weak neutral current contribution was calculated in the Glashow–Weinberg–Salam (GWS) theory [19]. The expression was given in ref. [20] and can be found e.g. in ref. [3] [‡3]. In the GWS theory $\sin^2\theta_W$ is the only free parameter. It determines the weak neutral current vector couplings of electrons and quarks, $g_V^{e,q} = \pm\frac{1}{2} - 2Q\sin^2\theta_W$ (the minus sign applies to electrons and quarks with charge $Q = -1/3$, the plus sign to quarks with $Q = 2/3$), and the Z^0 mass ($M_Z = 74.6$ GeV$/\sin 2\theta_W$) and therefore the neutral current propagator.

We performed two types of fits to determine the weak contribution, (a) the $g_V^{e,q}$ and M_Z were expressed in terms of $\sin^2\theta_W$; (b) the $g_V^{e,q}$ were expressed in terms of $\sin^2\theta_W$ while M_Z was taken to be 95 GeV, a value consistent with the measurement of ref. [21]. Both fits yielded the same result, $\sin^2\theta_W = 0.30^{+0.23}_{-0.07}$ [‡4] for $\chi^2/\mathrm{DOF} = 10.7/16$. The value for $\sin^2\theta_W$ agrees well with our result obtained from e^+e^- scattering for purely leptonic reactions ($e^+e^- \to e^+e^-, \mu^+\mu^-$) $\sin^2\theta_W = 0.27 \pm 0.07$ [22] and with the values obtained by other e^+e^- experiments [‡5]. It

‡3 The cross section expression given in ref. (3) contains two misprints. The correct expressions for σ_{VV}^q, and σ_{aa}^q read:

$$\sigma_{VV}^q = \tfrac{1}{2}(3\beta - \beta^3)\,[(4\pi\alpha^2/s)e_q^2 + (4G_F\alpha/\sqrt{2})e_q g_V^e g_V^q \mathrm{Re}(\chi) + (G_F^2/2\pi)(g_V^{e2} + g_a^{e2})g_V^{q2} s|\chi|^2] ,$$

$$\sigma_{aa}^q = \beta^3 (G_F^2/2\pi)(g_V^{e2} + g_a^{e2})g_a^{q2} s|\chi|^2 .$$

‡4 The result is rather insensitive to the value of α_s.

‡5 For a review see ref. [24].

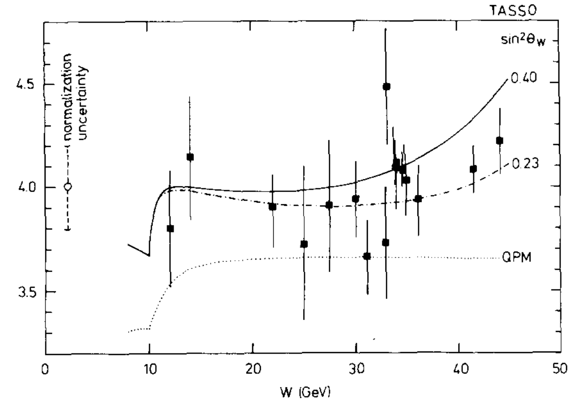


Fig. 3. The ratio $R = \sigma_{tot}/\sigma_{\mu\mu}$. The errors shown include the statistical and the point-to-point systematic uncertainty but not the overall normalization uncertainty of $\pm 4.5\%$. The dotted line shows the expectation from the quark–parton model (QPM). The full line and the dashed–dotted lines represent the QCD plus electroweak predictions for $\sin^2\theta_W = 0.23$ and 0.40, assuming α_s (s = 1000 GeV^2) = 0.18.

also agrees with the value obtained from neutrino scattering, $\sin^2\theta_W = 0.23 \pm 0.01$ [25]. We conclude that the data in R are consistent with the GWS predictions for the quark weak neutral current couplings (see fig. 3).

In summary, measurements of R have been presented for CM energies between 39.8 and 45.2 GeV. No evidence has been found for the existence of a narrow (< 10 MeV) state in this energy range. The 95% CL upper limit on the cross section contribution from such a state is $\int \sigma \, dW < 30.0$ nb MeV. The corresponding upper limit for the partial width times hadronic branching ratio is $\Gamma_{ee} B_h < 2.4$ keV (95% CL). This is considerably lower than the value of 3.5 keV expected for the lowest vector toponium state. From the measured R values and the observed event topologies lower limits have been derived for the threshold of top quark continuum production. At 95% confidence the threshold is above $W = 44.0$ GeV. The corresponding limit for pair production of charge 1/3 quarks is 42.0 GeV. This leads to lower mass limits of 22.0 GeV for top quarks and of 21.0 GeV for charge 1/3 quarks. Quarks have been found to be pointlike down to distances of 7×10^{-17} cm, the mass parameter being larger than 288 GeV. The previous lower limits have been 186 GeV (ref. [3]) and 239 GeV (ref. [26]), respectiveyl. The comparison of the R values for $W \geq 14$ GeV with the predictions of second order QCD and of the GWS theory for the weak neutral current yielded $\sin^2\theta_W = 0.30^{+0.23}_{-0.77}$.

The analysis reported here has been made possible by the indefatigable efforts of the machine group to push PETRA to its maximum energy. We thank the DESY directorate for the support of the experiment.

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