A MEASUREMENT OF σ_{tot} ($e^+e^- \rightarrow$ HADRONS) FOR CM ENERGIES BETWEEN 12.0 AND 36.7 GeV

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Received 8 March 1982

The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{\mu\mu}$ was measured between 12.0 and 36.7 GeV c.m. energy W with a precision of typically ± 5.2%. R is found to be constant with an average of $R = 4.01 \pm 0.03$ (stat.) ± 0.20 (syst.) for $W \geqslant 14$ GeV. Quarks are found to be point-like, the mass parameter describing a possible quark form-factor being larger than 186 GeV. Fits including QCD corrections and a weak neutral-current contribution are presented.

The total cross section, σ_{tot}, for e^+e^- annihilation into hadrons is a quantity of fundamental importance. In the quark–parton model σ_{tot} measures the sum of the squares of the quark charges e_q,

$$R \equiv \sigma_{\text{tot}}/\sigma_{\mu\mu} = 3 \sum_q e_q^2, \tag{1}$$

where $\sigma_{\mu\mu} = 4\pi\alpha^2/3s$ (s = square of total c.m. energy W) is the cross section for muon pair production by e^+e^- annihilation. The energy dependence of R can be used to test for a possible structure of quarks. QCD modifies the quark–parton prediction and precise measurements of R at high energies offer a particularly clean test of the theory. At high energies R also becomes sensitive to a possible contribution from the weak neutral current. The expected modifications due to both, QCD and the weak neutral current are small and their detection requires high-precision data. The accuracy of published R data in general is limited not by statistics but by systematic uncertainties which typically are of the order of 10%. In this letter we present high-energy measurements of R where a spcial effort was made to reduce the systematic errors to a level of 5%.

The experiment was performed at the DESY e^+e^- storage ring PETRA with the TASSO detector at c.m. energies W between 12.0 and 36.7 GeV, collecting approximately 16 000 hadronic annihilation events for a total integrated luminosity of ≈42 000 nb^{-1}. The detector as well as the data taking and analysis procedures have been described elsewhere [1,2].

The multihadron events were detected in the central detector using the information on charged particles. For those events used in this analysis the trigger required a minimum number of charged particles with polar angles θ measured with respect to the beam direction satisfying $|\cos\theta| < 0.82$ and having a minimum momentum p_{xy} perpendicular to the beam (z direction). The minimum number of tracks demanded was between 2 and 4; it was 2 for most of the high-statistics data at W = 14, 22 and 34 GeV. The nominal minimum p_{xy} was set to 0.22 GeV/c at 14 and 22 GeV and partly at W = 35 GeV, and 0.32 GeV/c for all other energies. After event reconstruction charged tracks were accepted if they satisfied the following requirements [3]:

(a) Track is reconstructed in three dimensions.

(b) $d_0 < 5$ cm where d_0 is the distance of closest approach to the origin in the (x,y) plane.

(c) $p_{xy} > 0.1$ GeV/c.

(d) $|\cos\theta| < 0.87$.

(e) $|z - z_v| < 20$ cm, where z is the track coordinate at the point of closest approach to the beam and z_v is the z coordinate of the event vertex averaged over the tracks.

The events were required to obey the following criteria:

(1) At least 4 (5) accepted tracks for W = 12–25 GeV ($W \geqslant 27$ GeV).

(2) To suppress the contribution from τ pair production at $W < 15$ GeV ($W > 15$ GeV) events with 3 charged tracks in one hemisphere wrt the sphericity axis and 1 (1 or 3) in the other hemisphere were discarded if the effective mass of either particle system was less than the τ mass (assuming pion masses for the observed particles).

(3) For $W \leqslant 14$ GeV, tracks were required in both hemispheres defined with respect to the beam axis,

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and the sum of the charges of the accepted tracks was not to exceed 3.

(4) The z coordinate of the event vertex had to be $|z_{\mathrm{v}}| < 6$ cm.

(5) The momentum sum $\Sigma p \equiv \Sigma |p_i|$ of the particle momenta had to be $\Sigma p > 0.265\ W$.

These cuts discriminated against beam–gas scattering (3–5), τ pair production (1,2), Bhabha scattering and μ pair production (1) and $\gamma\gamma$ scattering (1,5). All events surviving these cuts were inspected visually. Approximately 3% were rejected, most of them being Bhabha scattering events producing electromagnetic showers in the material before the tracking chambers.

In the absence of radiative effects the value of the total cross section, σ_{tot}, at c.m. energy W follows directly from the number of events observed, N_{meas}, the number of background events, N_{bg}, the acceptance A and the luminosity $\mathcal{L}$:

$$\sigma_{\mathrm{tot}}(W) = \mathcal{L}^{-1}(N_{\mathrm{meas}} - N_{\mathrm{bg}})/A . \qquad (2)$$

In the presence of radiative effects A has to be weighted with the photon spectrum,

$$A = \int \mathrm{d}\boldsymbol{k}\, f(\boldsymbol{k})\, a(\boldsymbol{k}, W')\, \sigma_{\mathrm{tot}}(W')/\sigma_{\mathrm{tot}}(W), \qquad (3)$$

where $\boldsymbol{k}$ is the momentum vector of the photon emitted in the initial state. $f(\boldsymbol{k})$ describes the spectrum of photons emitted in the initial state with momentum vector $\boldsymbol{k}$ plus all other radiative corrections, W' is the c.m. energy of the hadronic system produced, $W' = (W^2 - 2W|\boldsymbol{k}|)^{1/2}$, $a(\boldsymbol{k}, W')$ is the acceptance for a hadronic system with c.m. energy W' and momentum $-\boldsymbol{k}$.

In the following we discuss the determination of the quantities that enter the expression for σ_{tot} and their systematic uncertainties.

The contamination from beam–gas scattering as determined from the vertex distribution along the beam and from an inspection of events with an excess of positively charged particles was found to be 0.5 ± 0.5% at $W \leqslant 15$ GeV and negligible at higher energies. The contribution of τ pair production was determined by a Monte Carlo method to be (1.5 ± 1.5)% at $W \leqslant 15$ GeV and (1.2 ± 1.2)% at $W \geqslant 15$ GeV. In assessing the contribution from $\gamma\gamma$ scattering, hadron–hadron type (VDM-like) scattering and hard scattering were considered. The parameters for the first process were adjusted to fit our data on the total $\gamma\gamma$ cross section. The parameters for the hard scattering were determined with the help of the $\gamma\gamma$ events with high transverse momenta [4]. The background from $\gamma\gamma$ processes was found to be (1.6 ± 0.8)% at all energies where the error reflects the estimated systematic uncertainty. The contribution from Bhabha scattering was eliminated by visual inspection. After all corrections the corrected number of accepted events has a systematic uncertainty between 1.8% (W = 14 GeV) and 1.5% (W = 34 GeV).

The trigger efficiency ϵ was computed from the trigger efficiency for a single track measured as a function of p_{xy} and $\cos\theta$. A Monte Carlo program was then used to evaluate the trigger efficiencies for events satisfying criteria (1)–(5). This yielded for W = 14, 22 and 34 GeV, ϵ = (98.4 ± 1.0)%, (98.1 ± 1.0)% and (99.1 ± 1.0)%, respectively. An additional check of the trigger efficiency came from a neutral trigger which required an energy deposition of at least 2 GeV in one of the barrel or hadron arm shower counters (which cover 60% of the solid angle). Consistent results were obtained.

The acceptance for the off-line selection criteria (1)–(5) was calculated by a Monte Carlo method, generating events [5] according to $\mathrm{e^+e^-} \to \mathrm{q\bar{q}}$ and $\mathrm{e^+e^-} \to \mathrm{q\bar{q}g}$ using Field–Feynman fragmentation functions [6]. Baryon production was also included [7]. The fragmentation parameters [‡1] were determined previously by this experiment and were found to describe well the charged-particle data [8]. The generated events were followed through the detector producing e.g. the hits in the track chambers. The events were then passed through the track reconstruction and acceptance programs used for the real data. In the absence of radiative effects the acceptance including trigger and off-line selection was found to vary from 77% at W = 14 GeV to 79% at W = 34 GeV.

[‡1] Due to our acceptance criteria the contribution to R from the two-body channels $\mathrm{e^+e^-} \to \pi^+\pi^-$, $\mathrm{K^+K^-}$ and $\mathrm{p\bar{p}}$ are not included, nor are they taken into account in the Monte Carlo model. We searched for these contributions following our study of muon pair production [9]. Candidate events were selected by requiring two collinear tracks, each with less than 1.5 GeV energy deposited in the liquid argon calorimeter. In order to exclude muon pairs and to suppress τ pair production, events were discarded which had hits in the muon chambers following the calorimeter. The R value for pair production of charged hadrons (π, K, p) was found to be $R < 0.03$ (95% CL).

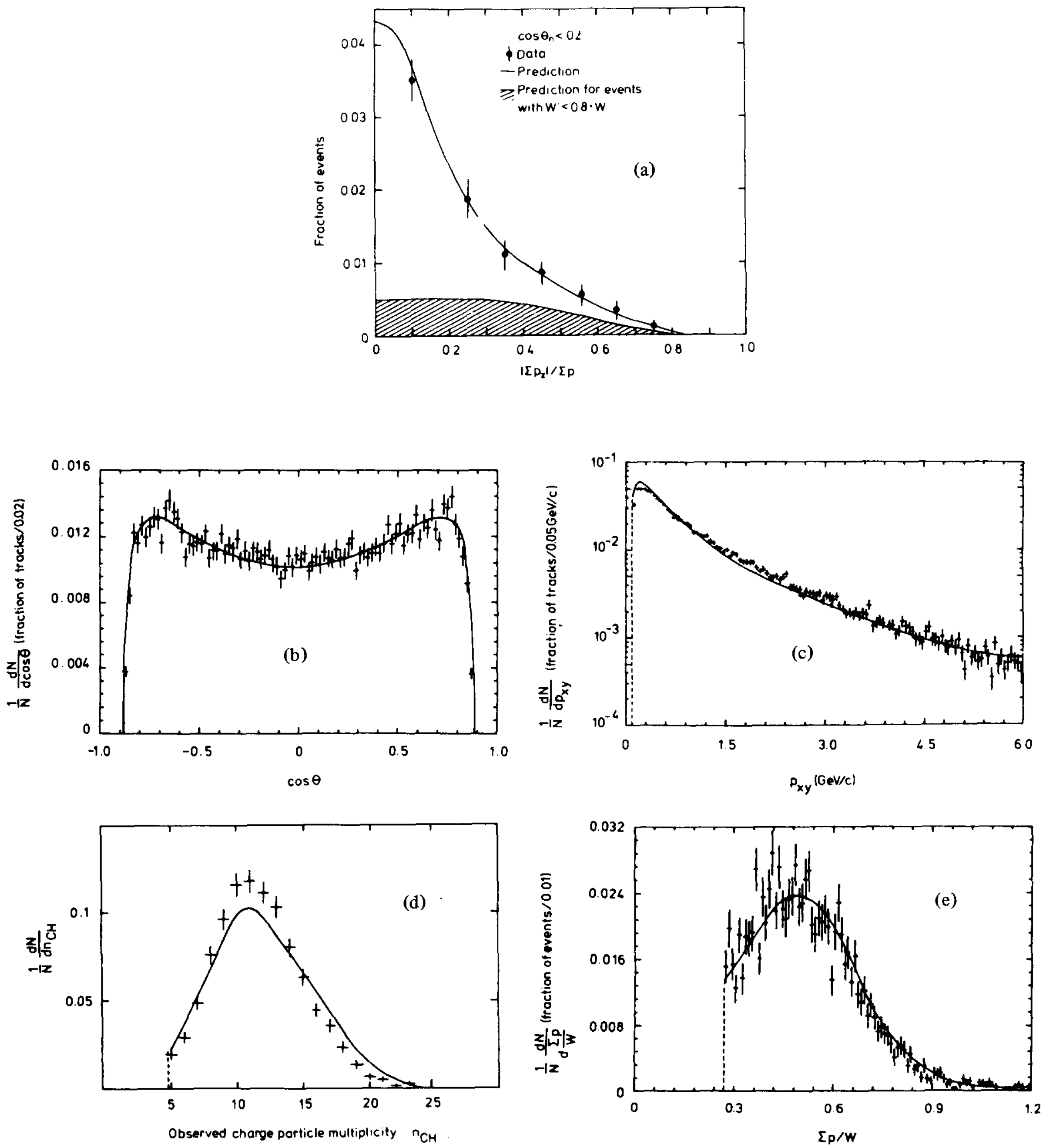

Fig. 1. Distributions relevant for the selection of multihadron events. (a) The fraction of accepted events at $W = 14$ GeV with $\cos\theta_n < 0.2$ as a function of $|\Sigma p_z|/\Sigma p$. The solid curve shows the prediction of the Monte Carlo model (see text). The dashed area shows the prediction for events with hard photon bremsstrahlung, $W' < 0.8$ W. (b,c) Distributions of $\cos\theta$ (a) and p_{xy} (b) for accepted charged particles. The solid curves show the predicted distributions. (d,e) Distributions of the observed charged-particle multiplicity n_{CH} (d) and the normalized momentum sum $\Sigma p/W$ (e) for accepted events.

The radiative effects were calculated with a computer program by Berends and Kleiss [10] which was incorporated in the Monte Carlo event generator mentioned above. Initial-state radiation and vertex corrections as well as vacuum polarization were included. The precision of the radiative-correction calculation is affected by the omission of higher-order terms and of final-state radiation, and above all by uncertainties in σ_{tot} and the description of the final states at $W' \ll W$. σ_{tot} enters in the calculation of the hadronic vacuum polarization (which increases the observable cross section by $\approx 5\%$) and of photon emission by the incoming electron (positron): at a nominal energy of $W = 14$ GeV roughly 15% of the accepted events are produced at $W' < 12$ GeV. However, since these events have an energetic photon emitted predominantly at small angles, they populate a specific kinematical region. This permits a test of the corresponding radiative correction. To define the kinematical region in question note first that for two-jet events with a hard collinear photon emitted in the initial state the two jets lie in a plane which contains the beam axis. Furthermore, summing over all accepted charged particles, the momentum imbalance along the beam axis, $|\Sigma p_z|$, is particularly large for these events. Using the sphericity tensor, the event plane and the angle θ_n between the normal to the event plane and the beam axis were calculated. For the $W = 14$ GeV data which are particularly affected by the uncertainties in the radiative corrections, fig. 1a shows the distribution of $|\Sigma p_z|/\Sigma p$ for events with $|\cos\theta_n| < 0.2$. The Monte Carlo prediction is shown by the solid curve which is seen to describe the data well. The shaded area shows the Monte Carlo prediction for "radiative" events having $W' < 0.8\,W$; they are seen to be important at large $|\Sigma p_z|/\Sigma p$. For $|\cos\theta_n| < 0.2$ and $|\Sigma p_z|/\Sigma p > 0.2$ the predicted fraction of events is 4.8% (3.1% with $W' > 0.8\,W$ and 1.7% with $W' < 0.8\,W$) which is in agreement with the observed $(4.8 \pm 0.4)\%$. Good agreement is also obtained at all other energies, e.g. at 30–36 GeV the predicted fraction of events is 8.8% compared to $(9.0 \pm 0.5)\%$ observed. The total radiative effects considered change the weighted acceptance A as defined in eq. (3) e.g. at $W = 34$ GeV by 15% from $A = 79\%$ (no radiative effects) to $A = 91\%$. The higher-order radiative effects were not included; they can be expected to be of the order $(0.15)^2 \approx 2\%$. A detailed calculation does not exist but is under study [11]. We estimate that the uncertainties in the radiative corrections contribute in total a ±2.5% systematic error to σ_{tot}.

As a check of how well we understand the trigger efficiency, the acceptance and the radiative effects, we display in figs. 1b–e for the data at $W = 34$ GeV the distributions of those quantities which were used in the track and event selection, $\cos\theta$ and p_{xy} for accepted charged particles, the observed charged-particle multiplicity, n_{CH}, and the normalized momentum sum over all observed particles, $\Sigma p/W$. The Monte Carlo predictions are indicated by the curves. The single-particle distributions for $\cos\theta$ and p_{xy} are reproduced. The distributions of n_{CH} (fig. 1d) and $\Sigma p/W$ (fig. 1e) show that the fraction of events lost is small and that the Monte Carlo model used permits a reliable determination of the acceptance. The predicted n_{CH} distribution is broader than the observed one. The prediction for $\Sigma p/W$ describes the data well except for a small shift (≈ 0.015) to higher values. The discrepancies are included in the estimate of the systematic error.

The systematic uncertainty in the acceptance A due to the selection criteria was estimated in several ways: (a) by varying the fragmentation parameters within their errors [8] [‡2]; (b) by varying the cuts in the multiplicity and in Σp separately and together. Varying these cuts within reasonable limits had only a small effect on the value of σ_{tot}: e.g. at $W = 34$ GeV increasing the p_{xy} cut from 0.1 GeV/c to 0.25 GeV/c changed σ_{tot} by less than 0.8%, or raising the multiplicity cut continuously from 5 to 11 charged particles changed σ_{tot} by at most 2.4%. We estimate these uncertainties to be 3.5% at the lowest energy decreasing to 2.5% at the highest energy.

The luminosity $\mathcal{L}$ was determined from Bhabha scattering observed in the forward detector ($\mathcal{L}_{\mathrm{F}}$) centered at scattering angles around 2°, and independently in the central detector ($\mathcal{L}_{\mathrm{C}}$) accepting $|\cos\theta| < 0.8$ (see ref. [13] for details). Radiative corrections were applied [10]. They amounted to 1 ± 2% and 5 ± 1.5%, respectively. The systematic uncertainties in the two measurements were different. Apart from the radiative corrections the main sources of uncertainties in

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[‡2] To analyse the model dependence of the acceptance A we studied A also in the Lund model (ref. [12]). Choosing the parameters such as to describe the data the differences in A were found to be within the quoted uncertainties.

the case of $\mathcal{L}_F$ were uncertainties in the counter positions (±0.7%), interactions of the electrons in the material in front of the counters (±2%), backscattering from the shower counters (±1%) and subtraction of background (±2 to ±4%). The systematic error of $\mathcal{L}_F$ varied between 4.0 and 6.0%. For $\mathcal{L}_C$ the systematic error was determined mainly by uncertainties in the efficiencies for triggering (±0.5%), track reconstruc-

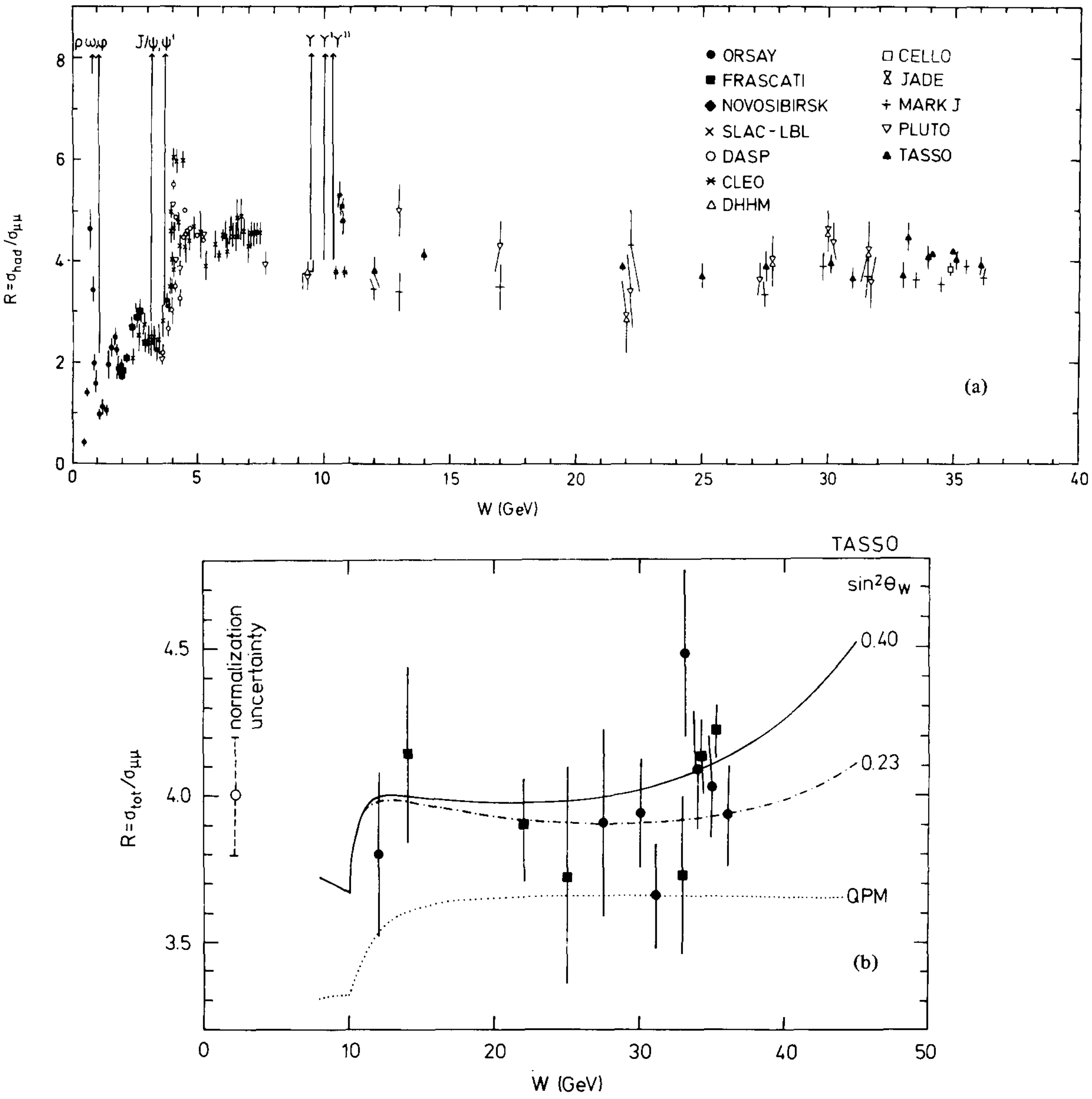

Fig. 2. (a) The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{\mu\mu}$ where $\sigma_{\mu\mu} = 4\pi\alpha^2/3s$. The data from other experiments were taken from refs. [19,28,30,31]. Only statistical errors are shown. (b) The same as in (a) with the measurements from this experiment, from runperiod I (1979) and 1980) (solid dot), and runperiod II (1981) (solid square). The errors shown include the statistical and the point-to-point systematic uncertainty but not the overall normalization uncertainty of ±4.5% which is shown separately. The dotted line shows the expectation from the quark–parton model (QPM). The full line represents the results from the fit and weak contributions (see text). The dashed–dotted line was computed with α_s ($s = 1000\ \mathrm{GeV}^2$) = 0.18 and $\sin^2\theta_W = 0.23$.

tion (±0.5%), event selection (±2%) and interactions of electrons in front of the drift chamber (±2%). The systematic uncertainty of $\mathcal{L}_C$ for most of the data was 5.0%. Since both luminosity measurements agreed with each other well within their systematic errors the two results were averaged yielding $\mathcal{L}$ with a systematic uncertainty between 3.1 and 4.0% for most of the data.

Adding all systematic errors (e.g. at $W = 34$ GeV, trigger 1%, background 1.5%, radiative corrections 2.5%, loss of acceptance by selection criteria 2.5%, luminosity 3.4%) in quadrature the total systematic error for most of the data is typically 5.2% of which 4.5% represent an overall normalization uncertainty which is independent of W and 2.7% represents the point-to-point uncertainty.

Results. We present in fig. 2 the corrected R values. A fraction of the data between 29.9 and 36.7 GeV has been taken in the scanning mode changing the c.m. energy W in steps of 0.02 GeV. For presentation in fig. 2 they have been averaged over W regions of typically 1.0 GeV width. The errors shown for our data include the statistical as well as the systematical errors except for the overall normalization uncertainty of $\sigma_{\text{norm}} = 4.5\%$ which is not shown. The total error is typically 5–6% per data point. Also shown in fig. 2 are total cross-section data from other experiments.

In the following we compare our data to various theories and models.

Step in R. The data between 14 and 36.7 GeV are consistent with a constant value of R, the average being $R = 4.01 \pm 0.03$ (stat.) ± 0.20 (syst.) for $W \geqslant 14$ GeV. The data set limits on the contribution from pair production of new particles which is $\Delta R = \beta(3 - \beta^2)/2\Delta R_0$ for spin 1/2 partons and $\Delta R = \beta^3 \Delta R_0$ for scalar partons where β is the parton velocity, $\beta = p/E$. Under the assumption that the final states produced by the partons have a similar acceptance as for the average hadronic final states we obtain for parton masses between 12.5 and 17 GeV $\Delta R_0 < 0.39$ ($\Delta R_0 < 0.50$) for spin 1/2 (spin 0) partons with 95% CL. This excludes e.g. a top-quark contribution ($\Delta R_0 = 4/3$) in agreement with event-shape studies which also render the presence of a new charge 1/3 quark contribution unlikely [2,14]. We also note that production of new heavy charged leptons of the standard type, of neutral heavy leptons or of scalar leptons in this energy range have already been ruled out [15].

Narrow states. Fig. 3 shows R measured in steps of 0.02 GeV between 33.00 and 36.70 GeV in a search for narrow states. The step size is close to the c.m. energy spread produced by quantum fluctuations of the beam,

$$\sigma_W(\text{GeV}) = 2.2 \times 10^{-5}\, W^2\ (\text{GeV}^2),$$

or $\sigma_W = 27$ MeV at $W = 35$ GeV. The average beam energy was monitored to an accuracy of $\sim 10^{-4}$ or 3 MeV in W. On the average there are 11 hadronic events per data point. No statistically significant struc-

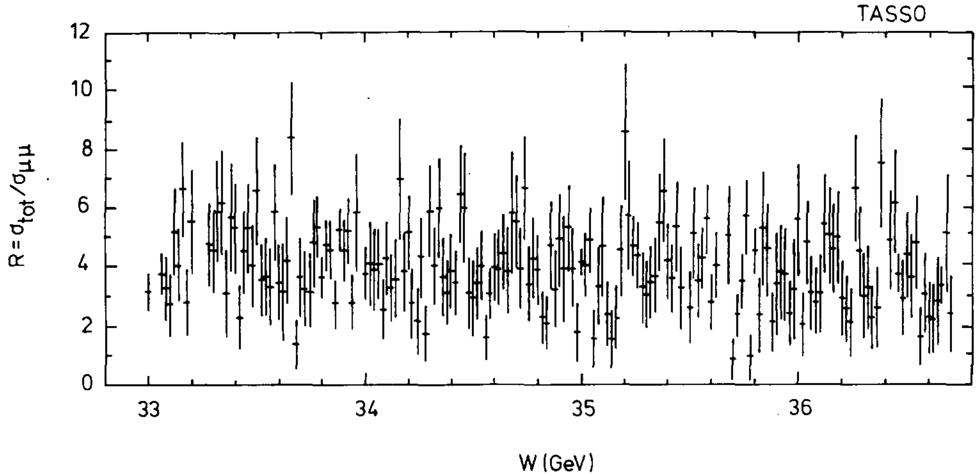

Fig. 3. The ratio $R = \sigma_{\text{tot}}/\sigma_{\mu\mu}$ measured in the scanning mode between 33.0 and 36.7 GeV.

ture is observed. Proceeding as in ref. [16] where our scan results are reported for the region 29.90 to 31.46 GeV, an upper limit on the cross-section contribution of a narrow ($\Gamma < 10$ MeV) state of

$$\int \sigma \, \mathrm{d}W < 31 \text{ nb MeV} \quad (95\% \text{ CL})$$

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

$$\Gamma_{ee} B_h < 1.5 \text{ keV} \quad (95\% \text{ CL}) .$$

It excludes the presence of a vector ground state $Q\bar{Q}$ for charge 2/3 quarks for which $\Gamma_{ee} \simeq 5$ keV and $B_h \simeq 0.7$ is expected [17] while a charge 1/3 $Q\bar{Q}$ state cannot be ruled out ($\Gamma_{ee} \simeq 1.3$ keV, $B_h \simeq 0.7$). However, by combining with the results from other PETRA experiments [14,15,18] one obtains $\Gamma_{ee} B_h < 0.7$ keV which excludes also the latter possibility.

As a result of the preceeding discussion we attribute the measured R values exclusively to the production of the five quarks u, d, s, c and 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 [19]

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

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 $\sin^2\theta_W = 0.228$, see below) the data for $W \geqslant 14$ GeV yield $M > 186$ 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 $M_D > 264$ GeV (95% CL). The result can also be expressed in terms of cut-off parameters, $G_M(s) = 1 \mp s/(s - \Lambda_\pm^2)$, which yields $\Lambda_+ \equiv M > 186$ GeV and $\Lambda_- > 363$ GeV.

Comparison with QCD and weak contributions. In QCD the quark–parton result for R is modified by gluonic corrections which in second order lead to

$$R = 3 \sum e_q^2 [1 + \alpha_s/\pi + C_2(\alpha_s/\pi)^2] , \qquad (4)$$

where $C_2 = 1.39$ in the $\overline{\text{MS}}$ scheme [20], R can also receive contributions from the weak neutral current, for which evidence was found recently in the reaction $e^+e^- \to \mu^+\mu^-$ [9,21]. The expression for σ_{tot} which accounts for QCD corrections, for finite quark masses and for the weak neutral-current contribution as predicted by the Weinberg–Salam theory is given by [22]

$$R = \frac{1}{\sigma_{\mu\mu}} \sum_q \{[1 + C_1^v \alpha_s/\pi + C_2^v(\alpha_s/\pi)^2]\, \sigma_{vv}^q$$
$$+ [1 + C_1^a \alpha_s/\pi + C_2^a(\alpha_s/\pi)^2]\, \sigma_{aa}^q\} , \qquad (5)$$

where ‡3

$$C_1^v = \tfrac{4}{3}\pi\{\pi/2\beta_q - [(3 + \beta_q)/4](\pi/2 - 3/4\pi)\} ,$$

$$\beta_q = (1 - 4m_q^2/s)^{1/2} , \quad C_1^a = 1 , \quad C_2^v = C_2^a = 1.39 , \qquad (6)$$

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

$$\sigma_{aa}^q = \beta^3 (G_F^2/4\pi)(g_v^{e\,2} + g_a^{e\,2}) g_a^{q\,2} s|\chi|^2 ,$$

G_F is the Fermi coupling constant,

$$\chi = M_z^2/(M_z^2 - s + iM_z\Gamma_z) , \quad M_z = 74.6 \text{ GeV}/\sin 2\theta_W ,$$

$$g_v^{e,q} = \mp\tfrac{1}{2} - 2Q\sin^2\theta_W , \quad g_a^{e,q} = \mp\tfrac{1}{2} ,$$

the minus sign in the expressions for $g_v^{e,q}$, $g_a^{e,q}$ applies to electrons ($Q = -1$) and quarks with charge $Q = e_q = -1/3$, the plus sign to quarks with $Q = e_q = 2/3$. The energy dependence of α_s was described in terms of the QCD parameter Λ using the second-order formula [20].

We made a χ^2 fit to our data at $W \geqslant 14$ GeV (which is expected to be well above the $b\bar{b}$ resonance region) in order to determine α_s and $\sin^2\theta_W$. The χ^2 was defined such as to account for the fact that part of the systematical error is due to the overall normalization uncertainty, σ_{norm}:

$$\chi^2 = (F - 1)^2/\sigma_{norm}^2 + \sum [R_i F - R(\alpha_s, \sin^2\theta_W)]^2/\sigma_i^2 , \qquad (7)$$

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‡3 The values used for m_q are $m_u = m_d = 0.3$ GeV, $m_s = 0.5$ GeV, $m_c = 1.5$ GeV and $m_b = 5.3$ GeV. For C_1^a a numerical evaluation is given in ref. [22]. The approximation $C_1^a = 1$ has a negligible effect on our analysis. The coefficient C_2^a has not yet been evaluated and $C_2^a = C_2^v$ was assumed.

where the R_i are the measured R values with errors σ_i (not including σ_{norm}), and F is the overall normalization factor treated as a free parameter. Since α_s is found to be small, F and α_s are completely correlated. The fit was therefore done with F set to $F = 1$ yielding α_s ($s = 1000\ \mathrm{GeV}^2$) = 0.18 ± 0.03 ± 0.14, $\sin^2\theta_W = 0.40 \pm 0.16 \pm 0.02$ with a $\chi^2 = 12.1$ for 11 d.o.f. The second errors given reflect the error due to σ_{norm}. The fit result is shown by the solid curve in fig. 2b. Assuming $\sin^2\theta_W = 0.228$ as measured in lepton-scattering experiments at lower energies [23] the fit gave α_s ($s = 1000\ \mathrm{GeV}^2$) = 0.24 ± 0.05 ± 0.13. Measurements of three-jet production in e^+e^- annihilation yielded in first-order QCD $\alpha_s \simeq 0.17$ [8,24] for $s \approx 1000\ \mathrm{GeV}^2$. Second-order corrections give either $\alpha_s = 0.17$ [25] or $\alpha_s = 0.12$ [26]. Assuming $\alpha_s = 0.17$ (0.12) the fit yielded $F = 1.00 \pm 0.04$ (1.01 ± 0.04) and $\sin^2\theta_W = 0.40 \pm 0.15 \pm 0.02$ (0.39 ± 0.14 ± 0.02). Our results on α_s and $\sin^2\theta_W$ are consistent with those obtained in refs. [27,28].

If we take the weak-coupling constants g_a, g_v as measured in lepton scattering [29] [i.e. g_a, g_v as given in eq. (7) with $\sin^2\theta_W = 0.228$] and assume $\alpha_s = 0.17$ the data yield a lower limit on M_Z, $M_Z > 45$ GeV (95% CL). The result is unchanged if $\alpha_s = 0.12$ is used.

Conclusion. R has been measured for c.m. energies between 12 and 37 GeV with a precision of typically ±5.2% systematical uncertainties. R is found to be constant within errors with an average value of $R = 4.01 \pm 0.03 \pm 0.20$ for $W \geqslant 14$ GeV. The data exclude a step in R of $\Delta R_0 > 0.39$ for spin 1/2 parton pairs (> 0.50 for scalar parton pairs) with the threshold between 25 and 34 GeV. Measurements done in a scanning mode between 33.00 and 36.70 GeV have not revealed any narrow (< 10 MeV) structure. The integrated cross section of such a structure is < 31 nb MeV which excludes the presence of the expected vector ground state of toponium. Quarks have been found to be point-like, the mass parameter describing a possible quark form-factor being larger than 186 GeV. The R values of $W \geqslant 14$ GeV were compared with QCD and with the predictions of the Weinberg–Salam theory for the weak neutral current. The fit yielded for α_s evaluated at $s = 1000\ \mathrm{GeV}^2$, $\alpha_s = 0.18 \pm 0.03 \pm 0.14$ and $\sin^2\theta_W = 0.40 \pm 0.16 \pm 0.02$.

We want to thank the DESY directorate and in particular Professor V. Soergel and Professor G.A. Voss for the continuing support of the experiment. The tremendous efforts of the PETRA machine group are gratefully acknowledged. We thank the DESY Rechenzentrum and in particular Mr. Kuhlmann for help. Those of us from abroad wish to thank the DESY directorate for the hospitality extended to us while working at DESY.

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