PRECISE MEASUREMENT OF TOTAL CROSS SECTIONS FOR THE PROCESS $e^+e^- \to$ MULTIHADRONS IN THE CM ENERGY RANGE BETWEEN 12.0 AND 36.4 GeV

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The total cross section for the process $e^+e^- \to$ hadrons has been measured in the CM energy range between 12.0 and 36.4 GeV using the JADE detector with a typical systematic error of ±3%. The ratio R (σ(ee $\to$ hadrons)/σ_{pt}) is found to be constant over this range with an average value of 3.97 ± 0.05 (statistical and point-to-point systematic error) ± 0.10 (normalization error). The data were compared with the standard electro-weak interaction model including QCD corrections.

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R, the ratio of the hadron production cross section via single photon annihilation to the lowest order pointlike QED cross section [$\sigma_{pt} = (4\pi/3s)\,\alpha^2$], is a fundamental quantity in e^+e^- interactions. It is calculated in the quark–parton model as $R = 3\Sigma_q Q_q^2$, where Q_q is the quark electric charge, and the summation runs over all the produced flavours. If a new threshold for pair production of charge 2/3 (1/3) quarks besides u, d, s, c and b quarks is passed, R is increased by about 36% (9%); if quarks would have structure, a deviation from a constant R may be observed. By including the lowest order QCD corrections and the electro-weak effect R is modified [1] to

$$R(s) = 3\sum_q \{(1+C_1^V\alpha_s/\pi)\tfrac{1}{2}\beta(3-\beta^2)Q_q^2$$

$$-2s(1+C_1^V\alpha_s/\pi)\tfrac{1}{2}\beta(3-\beta^2)(\sqrt{2}G_F/16\pi\alpha)Q_q v_e v_q/$$

$$[(s/m_Z^2-1)+\Gamma_Z^2/(s-m_Z^2)]$$

$$+s^2[(1+C_1^V\alpha_s/\pi)\tfrac{1}{2}\beta(3-\beta^2)v_q^2+(1+C_1^A\alpha_s/\pi)\beta^3 a_q^2]$$

$$\times(G_F^2/128\pi^2\alpha^2)(v_e^2+a_e^2)/[(s/m_Z^2-1)^2+\Gamma_Z^2/m_Z^2]\}\,, \quad (1)$$

$$C_1^V = \tfrac{4}{3}\pi[\pi/2\beta-\tfrac{1}{4}(3+\beta)(\tfrac{1}{2}\pi-3/4\pi)]\,,$$

$$C_1^A = 1\,,\quad \beta=(1-4m_q^2/s)^{1/2}\,, \quad (2)$$

$$\alpha_s = 12\pi/(33-2N_f)\ln(s/\Lambda^2)\,, \quad (3)$$

where G_F is the Fermi weak constant, m_Z and Γ_Z are the mass and width of the Z^0 boson and m_q is the quark mass. v_e, v_q, a_e and a_q are the vector and axial-vector coupling constants which are given in the standard model by:

$$v_e = -1 + 4\sin^2\theta_W\,, \qquad a_e = -1\,,$$

$$v_u = v_c = 1 - \tfrac{8}{3}\sin^2\theta_W\,, \qquad a_u = a_c = 1\,,$$

$$v_d = v_s = v_b = -1 + \tfrac{4}{3}\sin^2\theta_W\,, \qquad a_d = a_s = a_b = -1\,.$$

α is the fine structure constant and α_s is the running strong coupling constant, which is related to the QCD scale parameter Λ by formula (3). The QCD corrections to first order increase R by about 5% if α_s (30 GeV) = 0.18 [2]. The effect of the weak neutral current is energy dependent. It increases R by 1.5% at $\sqrt{s}$ = 37 GeV, if we take the standard model predictions with $\sin^2\theta_W = 0.229$ [3]. For a meaningful comparison experimental errors as small as possible are needed. In this letter, we report precise measurement of the ratio R and compare the data with the model predictions.

The details of the JADE detector and the trigger conditions for multihadronic events are described in ref. [4]. An important feature of the detector is that it is sensitive to charged particles and photons over 97% and 90% of the full solid angle, respectively. Especially, the barrel part of the lead glass counters cover the angular range $|\cos\theta| < 0.80$ and the complete azimuthal range with practically no holes. The large acceptance together with the uniformity of the detector minimizes systematic effects.

The present analysis is based on an integrated luminosity of 38 pb^{-1} accumulated in 1979–1981 by the JADE detector. About 15 000 multihadronic events were obtained. Most of the data were taken above $\sqrt{s}$ = 30 GeV. A relatively small number of events was accumulated at 12, 14, 22 and 25 GeV, too.

The multihadronic events are triggered mainly by the following two types of triggers:

(a) Total shower energy >4 GeV (2 GeV at $\sqrt{s}<$ 20 GeV).

(b) Total shower energy >1 GeV (0.5 GeV at $\sqrt{s}<$ 20 GeV), at least two time-of-flight counters fired and at least one track found by the fast track finding logic in the central drift chamber.

For the triggered events, the following selection cuts were applied by an offline reduction program.

(1) Shower energy in the barrel part (E_{bar}) > 3.0 GeV at $\sqrt{s}>$ 24 GeV (>2.0 GeV at 16 < $\sqrt{s}$ < 24 GeV, >1.2 GeV at $\sqrt{s}$ < 16 GeV) or shower energy in each end cap (E_{ec+} and E_{ec-}) > 0.4 GeV at $\sqrt{s}$ > 16 GeV (>0.2 GeV at $\sqrt{s}$ < 16 GeV).

(2) At least 3 charged particles coming from the interaction region (a cylinder of radius 30 mm and length of ±350 mm along the beam direction (z)) and being detected in the track detector.

(3) Among the tracks at least two must have p_T > 0.5 GeV/c and at least 24 hit points along the trajectory in the central drift chamber.

The events which passed the above cuts were scanned visually by physicists. During the scanning, the number of charged particles was counted. In particular, e^+e^- pairs and secondary electromagnetic showers were eliminated, which had been incorrectly recognized as charged particles coming from the event vertex by the reduction program. The following criteria were required by the scanner.

(4) At least 4 charged particles coming from the interaction volume are recognized by the scanner.

(5) Among the tracks at least three must satisfy the same requirement as (3).

(6) If the events has only 4 charged particle tracks, three of them should not be in an opposite hemisphere to the fourth to reject τ-pair production candidates.

For the events in the selected sample, the visible energy ($E_{vis} = \Sigma |p_i|$) and the longitudinal momentum balance ($p_{bal} = \Sigma p_i^z / E_{vis}$) were calculated, where summations are taken over charged and neutral particles. Then the following cuts were applied to obtain the final sample for the multihadronic events.

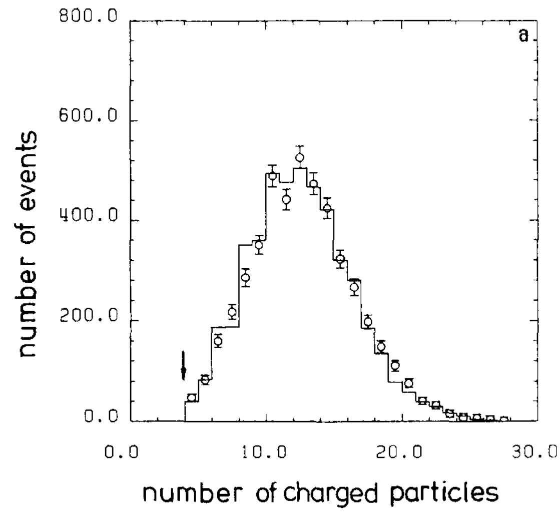
(8) $E_{vis} \geqslant$ beam energy ($= \frac{1}{2}\sqrt{s}$).

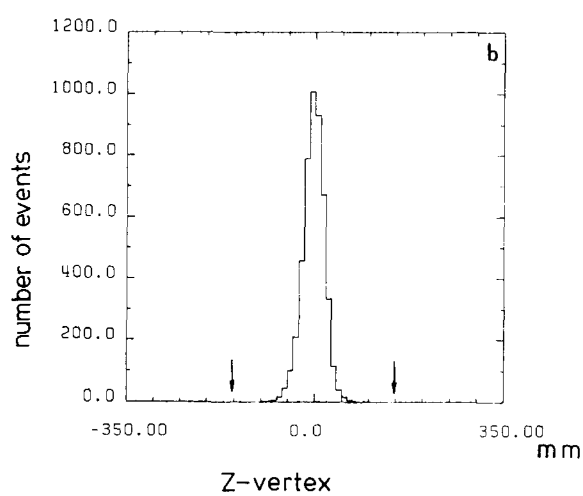
(9) $|p_{bal} \leqslant 0.4$.

(10) $|\text{Z-vertex}| \leqslant 150$ mm.

Distributions of some of the variables which are used for the cuts are shown in fig. 1 and are compared with distributions from the Monte Carlo simulation. The positions of the cuts are indicated by arrows.

The ratio R is calculated according to:





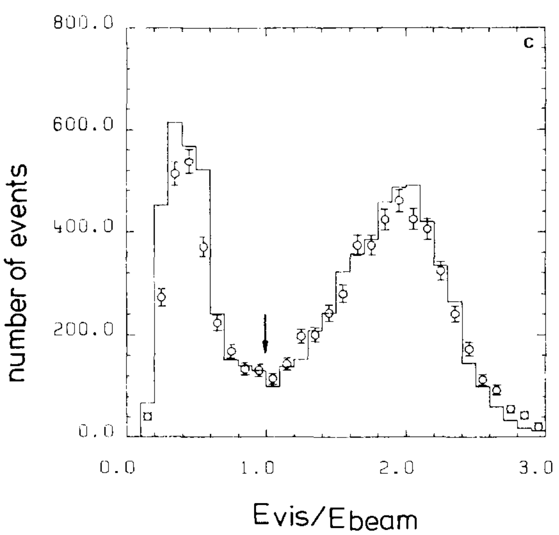


Fig. 1. (a) Distribution of the number of charged tracks coming from the fiducial volume. The histogram shows the prediction from the Monte Carlo simulation. (b) Z-vertex distribution after all other cuts. (c) Distribution of the visible energy after the cut on the p_{bal}. The histogram shows the prediction from the Monte Carlo simulations which include the hadron production process via single-photon annihilation and the VDM-like γ–γ interaction process.

$$R = (N - N_{bg})/[L\epsilon(1+\delta)]/\sigma_{pt}\,, \quad (4)$$

where N is the number of multihadronic events detected, N_{bg} is the estimated number of background events, L is the integrated luminosity, ϵ is the acceptance for the multihadronic events with radiative effect included and $1+\delta$ is the radiative correction factor due to higher order QED processes up to order α^3. All the quantities on the right hand side of the formula, except σ_{pt}, contain possible systematic errors. In the following, we estimate the individual systematic errors.

Events from beam–gas interaction were significantly eliminated by the cuts (1) and (9). As is clearly seen in the Z-vertex distribution for the events after all the cuts (fig. 1b), the remaining beam–gas background is negligible. Background from τ-pair production was estimated by a Monte Carlo simulation. Since at least 4 charged particles are required in the event selection, the possible background from τ-pair production are those events in which both of the τ's decay into $\geqslant 3$ charged particles, or events in which one τ decays into $\geqslant 3$ charged particles and the other into a single charged particle, which failed to be rejected in the scanning because of distortion of the event topology due to the initial radiation. Changing the τ-decay branching ratio $\mathrm{Br}(\tau \to \geqslant 3$ charge) in the Monte Carlo simulation from 10% to 24% [5], the estimated background changed from 0.9% to 3.9% (2.4% ± 1.5%) for $\sqrt{s}$ = 12–37 GeV. This includes the ambiguity introduced by the rejection of the 1 + 3 topology events by the scanners. Background from γ–γ processes was also estimated with Monte Carlo simulations [6] which include VDM-like and QED-like processes which are described by the Feynman diagrams of fig. 2. The VDM-like process (fig. 2a) tends to have low E_{vis} with an undetected electron and positron which escape into the beam pipe. Therefore, the background events from this process are well discriminated applying the cut on the E_{vis} distribution as is seen in fig. 1c. The background from this process was estimated to be 0.5% ± 0.5% at $\sqrt{s}$ = 35 GeV and negligibly small at $\sqrt{s}$ = 14 GeV. The error of ±0.5% comes mainly from an uncertainty in the assumed cross section $\sigma_{\gamma\gamma\to\mathrm{hadrons}}$, which we allowed to change by ±100%. Most of the background events from the QED-like γ–γ processes (fig. 2b) have a high energy electron or positron detected in the shower counters.

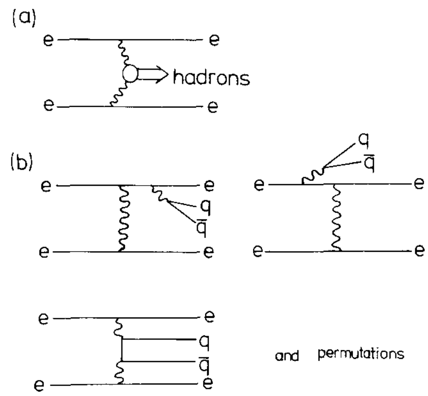


Fig. 2. Feynman diagrams of background γ–γ interaction processes. (a) VDM-like γ–γ scattering process. (b) QED-like γ–γ scattering process.

By the Monte Carlo simulation, the background from these processes was estimated to be 0.7% ± 0.5% for $\sqrt{s}$ = 12 to 37 GeV. The error was estimated by comparing the number of events from the simulation with the observed number of events which have an isolated high energy electron detected by the shower counters. Bhabha scattering, including ee → eeγ events was rejected by the cuts (2)–(5). The same cuts together with the Z-vertex cut (10) eliminate cosmic ray events. The remaining background from Bhabha scattering and cosmic rays is negligible.

The acceptance ϵ for the multihadronic events was calculated by a Monte Carlo simulation. In the simulation, the Lund model [7] was used together with the radiative corrections of Berends and Kleiss [8] to produce the initial radiation. The parameters in the model were chosen to give agreement with a study of charge multiplicity and neutral kaon production [9]. The model by Hoyer et al. [10] was found not to reproduce our experimental distributions, especially the charge multiplicity distributions [9]. For the simulated multihadronic events the same selection cuts (including the trigger conditions) as for the real events were applied. The acceptance ϵ was determined at various center-of-mass energies as a ratio of the number of events after the cuts divided by the number of generated events in the simulation. After multiplying the radiative correction factor, $\epsilon(1+\delta)$ = 1.03 for $\sqrt{s}$ = 35 GeV and 1.01 for $\sqrt{s}$ = 14 GeV.

It was found that the hardware trigger condition was so loose that the loss of events by the trigger was less than 1% with a negligibly small error. As is seen in fig. 1, all the selection cuts are fairly loose and the distributions are well reproduced by the simulation. Therefore systematic errors due to the selection cuts are estimated to be very small. This was checked by varying the cuts continuously within reasonable limits. For example, at $\sqrt{s}$ = 35 GeV, variation of the obtained R was within ±0.8% by moving the cut in E_{vis} from 1.0 to 1.6 times the beam energy; within ±0.5% by moving the cut in E_{bar} from 3 to 6 GeV; within ±0.8% by varying the other cuts and within ±0.8% by changing the value of α_s used in the simulation from 0.16 to 0.24 (value at 30 GeV). We estimate the total systematic error of R from the acceptance calculation to be 1.5% at $\sqrt{s}$ = 35 GeV and 2.5% at 14 GeV.

The formulae and the computer program provided by Berends and Kleiss were used to calculate the radiative correction factor $1 + \delta$ up to order α^3. Initial state radiation, vertex correction and vacuum polarization of e, μ, τ and hadrons were included in the corrections. The magnitude of the corrections at $\sqrt{s}$ = 35 GeV (14 GeV) amounted to: 11% (10%) from the electronic vacuum polarization including the vertex correction, 2.2% (1.6%) from μ and τ vacuum polarization, 4.7% (3.8%) from the hadronic vacuum polarization and 17.8% (8.5%) from the initial state radiation. The last number is dependent on the cut-off energy k_{max}, the maximum energy allowed for the radiated photon. In the simulation of events and in the calculation of the radiative corrections, k_{max} = 0.99 E_{beam} for $\sqrt{s} \geqslant 22$ GeV and k_{max} = 0.95 E_{beam} for $\sqrt{s} \leqslant 14$ GeV were used. The contributions to R from the region $k > k_{max}$ were calculated to be about 0.1% (0.15%) of R at $\sqrt{s}$ = 35 GeV (14 GeV). Uncertainties in the hadronic total cross sections used in the calculation affect the precision of the radiative corrections both in the initial state radiation part and in the hadronic vacuum polarization part. The systematic error from this origin was estimated to be ±0.8% (1.1%) at 35 GeV (14 GeV) assuming the input cross sections to have ±15% systematic uncertainties. Corrections due to QED process of order α^4 or higher are not included in the systematic error of R because no theoretical calculation is available yet.

The luminosity was measured using the process $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ detected by the barrel part of the lead glass shower counters. To avoid edge effect, the angular region was restricted to $|\cos\theta| <$ 0.76. There are few holes or discontinuities within this region; high energy electrons and photons can be detected with essentially 100% efficiency. The analysis of the events was done using only information from the lead glass counters, requiring two high energy showers, each with an energy greater than 1/3 of the beam energy, and with an acollinearity angle smaller than 10 degrees. Systematic errors in the luminosity measurement from various sources were estimated as follows:

The overall normalization error of the luminosity comes from the uncertainty in the acceptance and the radiative corrections. The accuracy of the detector geometry is believed to be better than ±5 mm. The resolution of the acollinearity angle measurement, which is crucial for the accuracy of the radiative corrections, was estimated to be less than ±1 degree; this error comes from the position resolution of the detected electrons by the lead glass counters. The measured luminosity is affected by ±1.5% due to these uncertainties.

The point-to-point error arises from the background subtraction, small gaps between the lead glass counter blocks, dead counters, energy calibration errors of the counters and the weak interaction effects. The background was estimated by Monte Carlo simulations of the multihadron production process, τ-pair production process and $e^+e^- \to e^+e^-e^+e^-$ process. A subset of the luminosity events was also scanned visually to estimate the background and to check the results of the Monte Carlo simulations. The difference between these two estimates was taken as the uncertainty in the background subtraction. The effect of small gaps between the counters was determined by selecting a set of Bhabha scattering events with one electron escaping through the gap. The effect of dead counters was checked by artificially omitting good counters (less than 12 counters and changing from period to period of the running). A possible energy calibration error, which is much less than a few percent, is not crucial to the luminosity measurement since the cut on the shower energy was fairly low. Variation of the luminosity due to the weak interaction effects was determined by varying the weak mixing angle $\sin^2\theta_W$ from 0.15 to 0.35.

The estimated point-to-point systematic error of the luminosity measurement from the above sources amounts to ±1.0%.

Table 1
Systematic errors of R.

	E_{CM}	
	≤ 14 GeV	22–37 GeV
background subtraction	±1.6%	±1.6%
radiative corrections	1.1	0.8
detection efficiency	2.5	1.5
luminosity point-to-point	1.0	1.0
luminosity overall normalization	1.5	1.5
total	3.6%	3.0%
point-to-point	2.7%	1.8%
overall normalization	2.4%	2.4%

A summary of the estimated systematic errors is given in table 1. Combining all the systematic errors quadratically, the total systematic error is ±3% (3.6%) at $\sqrt{s}$ = 35 GeV (14 GeV), where the overall normalization error contributes ±2.4% and ±1.8% (2.7%) is due to the point-to-point error.

The final R values are given in table 2 and in fig. 3. The data are averaged over typically 1 GeV bins of $\sqrt{s}$. The quoted errors include the statistical errors and the point-to-point systematic errors. The data between 12.0 and 36.4 GeV are consistent with a constant value of R with an average value $\langle R \rangle = 3.97 \pm 0.05 \pm 0.10$ (the second error is the overall normalization error). This value is in good agreement with the result of the TASSO group [11] $\langle R \rangle = 4.01 \pm 0.03 \pm 0.20$ and with other measurements performed in this energy range [12] as well as with recent results [13] from PEP at $\sqrt{s}$ = 29 GeV.

Table 2
Values for R. The errors quoted include the statistical and point-to-point systematic errors.

$\langle E_{CM} \rangle$ [GeV]	Number of events	Luminosity $[\mathrm{nb}]^{-1}$	$R \pm \Delta R$	
12.00	219	106.39	3.45	0.27
14.04	2649	1462.62	3.94	0.14
22.00	1871	2405.87	4.11	0.13
25.01	290	470.81	4.24	0.29
27.66	84	181.90	3.85	0.48
29.93	101	276.24	3.55	0.40
30.38	642	1664.35	3.85	0.19
31.29	251	693.09	3.83	0.28
33.89	3785	11279.52	4.16	0.10
34.50	570	1880.32	3.93	0.20
35.01	4162	13951.49	3.93	0.10
35.45	679	2362.49	3.93	0.18
36.38	420	1623.35	3.71	0.21

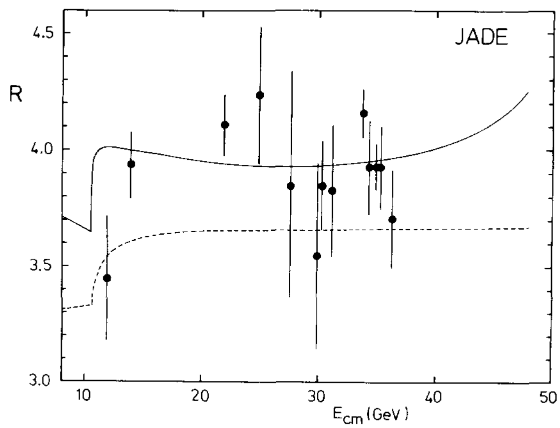


Fig. 3. The ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{pt}$. The error bars include the statistical and the point-to-point systematic errors. The solid curve represents the best fit to the formula (1) with α_s (30 GeV) = 0.20 and $\sin^2\theta_W$ = 0.23. The prediction from the simple quark–parton model is also shown by the dashed curve.

Limits for the pair production cross section of new quarks can be obtained from the data by assuming the contribution from them to be $\Delta R = \beta(3 - \beta^2)/2 \cdot \Delta R_0$, where $\beta = (1 - 4m_q^2/s)^{1/2}$ and m_q is the quark mass. If a similar acceptance is assumed for the final states produced by the new quark as for the usual multihadronic final states, the data give an upper limit $\Delta R_0 < 0.29$ for assumed quark masses between 7.5 and 17.5 GeV, at the 95% confidence level. With these limits top quark production, which gives $\Delta R_0 = 4/3$, is ruled out and production of a new charge 1/3 quark is unlikely.

The data can also be used to test the pointlike nature of quarks. Introducing a form factor $F(s)$, the data were fitted with the following formula:

$$R'(s) = R(s) \cdot |F(s)|^2 , \quad F(s) = 1 \mp s/(s - \Lambda_\pm^2) ,$$

where formula (1) is used for $R(s)$ with $\sin^2\theta_W$ = 0.229 and α_s (30 GeV) = 0.18. For each $\Lambda_\pm$, the overall normalization was adjusted to minimize the χ^2

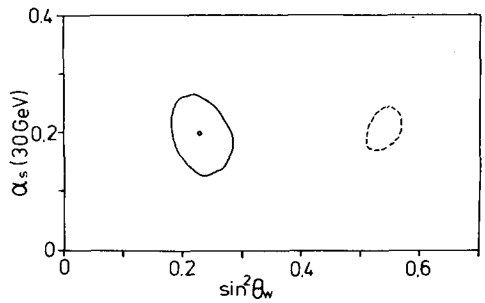


Fig. 4. Chi-squared contours in the $\sin^2\theta_W$–α_s (30 GeV) plane. (The contours correspond to an increase of 1 unit in the chi-squared.)

within the overall normalization error. For the cut-off parameters $\Lambda_\pm$, the fit yielded 95% confidence level lower bounds $\Lambda_- > 245$ GeV and $\Lambda_+ > 239$ GeV. Similar results were also obtained in ref. [11].

The data were fitted to the standard electro-weak interaction model using expression (1), leaving the QCD scale parameter Λ, the electro-weak mixing angle $\sin^2\theta_W$ and also the overall normalization factor f as free parameters. χ^2 is defined as follows:

$$\chi^2 = \sum [f \cdot R_i - R(s)]^2/\Delta R_i^2 + (f-1)^2/\sigma_{\text{norm}}^2 \, .$$

where R_i and ΔR_i are the experimental R-values and their errors (which include statistical and point-to-point systematic errors) and σ_{norm} is the overall normalization error. The data at 12 GeV were not used in the fit because of possible bottom-quark threshold effects. Fig. 4 shows χ^2 contours of this fit projected onto the α_s (30 GeV) $-\sin^2\theta_W$ parameter plane. The contours (solid and dashed lines) correspond to an increase of one unit in χ^2. The best fit was obtained at α_s (30 GeV) = 0.20 ± 0.08, $\sin^2\theta_W$ = 0.23 ± 0.05 and f = 0.99 ± 0.02 with χ^2 = 9.78 for 10 degrees of freedom. The errors include both statistical and systematic contributions, and give the one-standard deviation limits when the other parameters are left free. Using these best fit parameters, the theoretical R value [expression (1)] is drawn in fig. 3 as a solid curve. A second minimum of χ^2 exists at $\sin^2\theta_W$ = 0.54 and α_s (30 GeV) = 0.20 with the present data alone; it is excluded by an analysis of the lepton pair data of the same experiment [14]. These results are in good agreement with our previous determination [15] and with those obtained in refs. [11] and [16].

To summarize, R values were measured in the CM energy range between 12.0 and 36.4 GeV with systematic errors of typically ±3%. The data are consistent with a constant R in this energy range with an average value of 3.97 ± 0.05 (stat. and point-to-point sys.) ± 0.10 (overall). Corrections due to QED process of order α^4 or higher are not included. The data exclude a step in R of $\Delta R_0 > 0.29$ at the 95% confidence level, ruling out new charge 2/3 quark pair production with masses between 7.5 and 17.5 GeV. The data also set lower limits of $\Lambda_- > 245$ GeV and $\Lambda_+ > 239$ GeV (95% CL) to the cut-off parameters of the quark form factor. A fit to the standard electro-weak interaction model with QCD corrections yielded α_s (30 GeV) = 0.20 ± 0.08 and $\sin^2\theta_W$ = 0.23 ± 0.05.

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