ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
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НОВОСИБИРСК

The Measurement of R in e^+e^--Annihilation at Center-of-Mass Energies between 7.23 and 10.34 GeV *)

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ABTRACT

The total cross section of the process $e^+e^-\to hadrons$ has been measured in the center-of-mass energy range between 7.23 and 10.34 GeV using the MD-1 detector at the VEPP-4 collider. The ratio $R=\sigma(e^+e^-\to hadrons)/\sigma(e^+e^-\to\mu^+\mu^-)$ was found to be constant in this energy range with the average value of 3.58±0.02±0.14.

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1. INTRODUCTION

The ratio R is defined as $\sigma(e^+e^-\to hadrons)/\sigma(e^+e^-\to\mu^+\mu^-)$, where non-resonant hadronic cross-section does not include *QED* corrections and τ-pair decays, for μ-pair the Born cross-section is taken. In the quark-parton model the process $e^+e^-\to hadrons$ proceeds via quark-pair which fragment into hadrons and R is a sum of the squares of the quark charges. The high order *QCD* corrections increase the R value compared with simple quark-parton model. In the third order of *QCD* [1] the R value is given by :

$$R=3\sum_{i=1}^{n_f} Q_i^2\cdot f_i^0\cdot\left\{1+f_i^1\cdot\left[(\alpha_s/\pi)+r_1\cdot(\alpha_s/\pi)^2+r_2(\alpha_s/\pi)^3\right]\right\}, \qquad (1)$$

where n_f is the number of active quark flavours, the factor 3 is due to the number of quark colors. the factors f_i^0 and f_i^1 are connected with the threshold dependence of the $e^+e^-\to q\bar{q}$ cross-section [2]:

$$f_i^0=\beta_i\cdot\left[1+\frac{1}{2}(1-\beta_i)^2\right],$$

$$f_i^1=\frac{4\pi}{3}\left[\frac{\pi}{2\beta}-\frac{3+\beta_i}{4}\left(\frac{\pi}{2}-\frac{3}{4\pi}\right)\right].$$

The coefficients r_1 and r_2 obtained in the $\overline{MS}$ renormalization scheme are given in ref.[1]:

$$r_1 = 1.9857-0.1153\cdot n_f \ ,$$

$$r_2=-6.639-1.2001\cdot n_f-0.0052\cdot n_f^2- 1.235\cdot(\Sigma Q_i)^2/(3\Sigma Q_i^2) \ .$$

The expression (1) for R is valid at center-of-mass energies far below Z^0-mass where electroweek effects are negligible.

After the pioneering experiments in Frascatti [3,4] and in Novosibirsk [5], the process $e^+e^-\to hadrons$ was investigated in many experiments at different energies [6]. The interest to this process is connected with possibility of the test of *QCD* calculations and determination of the strong coupling constant in the way independent of fragmentation models.

In the present paper we report the results of the measurement of R at the center-of-mass energies between 7.23÷10.34 GeV using the MD-1 detector at the VEPP-4 collider. This region was not studied systematicaly before. The goal of the present experiment with MD-1 detector was a search for narrow resonances and precise measurement of the R in this energy region. Our result on the search for new narrow resonances was already published [7].

2. APPARATUS AND EXPERIMENT

The MD-1 detector has been described elsewhere [8÷10]. The magnetic field in the detector is transverse to the orbit plane. The field in the detector is proportional to the beam energy at VEPP-4 and is equal to 1.13T at E=4.7GeV. Starting from the interaction point the central part of the MD-1 detector contains the tracking system, the TOF scintillation counters, the threshold Cherenkov counters and the shower range chambers inside the magnetic coil. Outside the coil and yoke the muon system is situated. The tracking system contains 38 proportional chambers and covers the solid angle of $0.8\times4\pi$, the momentum resolution is $\sigma_p/p=(5\div15)\%\cdot p(GeV/c)$ in the solid angle $0.6\times4\pi$. The shower-range

system covers the solid angle $0.8\times4\pi$ and is built of 140 proportional chambers with 13 mm thick stainless steel cathode plates. The energy resolution for the photons is $\sigma_E/E=\{(20.5)^2/E+(12.6)^2\}^{1/2}\%$. The angular resolution is $\sigma_\Theta\cong\sigma_\Phi=(1\div2)^\circ$.

The beam energy of VEPP-4 was determined and periodically checked using the method of resonance depolarization of the particles [11]. The beam polarization was measured by means of scattering of the synchrotron radiation on the opositive beam [12]. Operative energy measurements were carried out using NMR and beam pick-ups. As a result in each run the c.m.s energy was known with accuracy better than 1 MeV.

The detector had a three level trigger. Information from the scintillation counters, shower-range and tracking systems was used for triggering. Two particles (including gamma quanta) out the orbit plane gave the trigger signal. The efficiency of the trigger was 96% for the process $e^+e^-\to hadrons$ in the continuum at $2E$=9.4 GeV. With currents of 7×7 nA^2 the luminosity of VEPP-4 was $3\cdot10^{30}\ cm^{-2}c^{-1}$ at E=4.7 GeV and the total trigger rate was 3 hz.

In order to exclude a possible dependence of the detection efficiency on the beam polarization the beams were kept unpolarized using the depolarizer. The special runs with separated beams were carried out for measurement of the background from beam-gas and beam-wall interactions. During 1984÷85 an integrated luminosity of 16 pb^{-1} was taken in the energy region 7.25÷10.34 *GeV*. The scanning was done with step of $\Delta(2E)$=4÷5 *MeV* (this value is close to the *c.m.s* energy spread at VEPP-4).

3. LUMINOSITY MEASUREMENT

The luminosity was measured using the elastic e^+e^--scattering at small angles (SA-monitor) [13]. This monitor provided good relative accuaracy (below 1.5 %) of the luminosity measurement. The absolute calibration of SA monitor was done during two runs by three independent methods: using double bremsstralung (DB) in a special experiment [13], the large angle e^+e^--scattering (LA) at $\Theta>45^\circ$ [12] and the process $e^+e^-\to\mu^+\mu^-$ (MM) [14]. In the Table 1 the results of this calibration are shown. It contains also the results of the relative calibration using elastic e^+e^--scattering at medium angles (MA, $12^\circ<\Theta<45^\circ$).

Table 1

The results of the SA monitor calibration

Method	Run	$\sigma_{SA}\times10^{29}\text{cm}^2$, $2E$=9.46 GeV		$\sigma^{(1)}_{SA}/\sigma^{(2)}_{SA}-1,[\%]$
DB	1	3.58±0.05±0.11		
LA	1	3.75±0.07±0.04	±0.6	6.8±3.3
	2	3.51±0.08±0.04		
MM	1	3.88±0.13	±0.06	8.9±3.6
	2	3.56±0.05		
MA	-	-		6.0±1.8

The cross section σ_{SA} of the SA monitor is different for the first and second runs. This difference is associated with the modification in the SA monitor during the shutdown between the runs. The integrated luminosity of 16 pb^{-1} for the measurement of R was taken during the second run. Using the results of the relative calibration by MA weighted value of $\bar{\sigma}_{SA}$ for the second run was obtained (at $2E$=9.46 GeV):

$$\bar{\sigma}_{SA}=(3.52 \pm 0.05)\cdot10^{-29}\text{cm}^2.$$

The comparison between the calibrations by central part of the detector (LA,MM) and by DB gives χ^2=1.8 for 1 degree of freedom. Applying a scale factor of $\sqrt{1.8}$ we obtained an 1.9% accuracy for the absolute calibration of the SA monitor.

The final value of the visible cross section $\bar{\sigma}_{SA}$ is:

$$\bar{\sigma}_{SA}=(3.52 \pm 0.07)\cdot\left(\frac{9.46}{2E(\text{GeV})}\right)^2\cdot10^{-29}\text{cm}^2 .$$

4. HADRONIC EVENT SELECTION

Two different sets of criteria were used to select hadronic events and to suppress backgrounds [15].

The first set of criteria ("T-criterion") is based, mainly, on the information from the tracking system. About 40% of all charged particles cross more than five chambers in the tracking system and can be reconstructed independently ("perfect particles"). In addition 30% of all charged particles cross less than 5 and more than 2 chambers ("imperfect particles") and can be reconstructed using the vertex position found with "perfect particles". For 15% of all charged particles only the direction can be determined. In the T-criterion, all events were divided into four classes depending on the number of the "perfect particles" N_p originated from the vertex of the event: N_p=0,1,2 and >3. In each class the different cuts were chosen using the following parameters:

$$P=\sum|p_i|,\quad P_z=\sum|p_{zi}|;\quad P_x=\sum|p_{xi}|/\sum|p_i| ,$$

where p_i, p_{xi}, p_{zi} are the particle momentum and its projections onto beam and magnetic field directions. The magnetic field in the detector was perpendicular to the orbit plane of the machine so the beam-wall background lies mainly in this plane and can be effectively suppressed with P_z cut. The P_x cut serves for suppression of the beam-gas and two-photon backgrounds. Typical cut values were less than 0.6 GeV/c.

The second set of criteria ("S-criterion") was designed in the same way, but the events were subdivided into 3 classes depending on the number of charged particles and photons reconstructed in the shower-range system. The cuts were applied to the parameters:

$$R=\sum r_i\ ,\quad R_z=\sum|r_i\cdot n_{zi}|\ ,\quad R_x=\sum|r_i\cdot n_{xi}|/\sum r_i\ ,$$

where r_i is a particle range (or longitudinal shower size for the photons) and (n_x,n_y,n_z) is an unit vector along the particle momentum.

The detection efficiencies of about 70% were obtained both with T and S-criterion for hadronic events in the continuum with the background level about 25% for both criterion. For further suppression of the background we required T and S-criterion simultaneously and applied some additional cuts:

1) $N_T+1.2\cdot N_S>6$ where N_T and N_S are numbers of the particles in the tracking and shower-range systems. This cut gives additional suppression of the two-photon, Bhabha and $e^+e^-\to\tau^+\tau^-$-processes.

2) $A_{sum}<630$ keV where A_{sum} is the energy deposition in the shower-range system. This cut rejects a background from Bhabha events.

As a result the detection efficiency of 52% was obtained at $2E=9.46$ GeV for the continuum events (see sec.6) with the background at the level of 5 % (see sec.5).

5. BACKGROUND

The following processes were considered as the sources of background:

1) Beam-wall and beam-gas interactions
2) $e^+e^-\to\mu^+\mu^-\gamma$
3) $e^+e^-\to e^+e^-\gamma$
4) $e^+e^-\to e^+e^-+e^+e^-$ ($\mu^+\mu^-$, $\tau^+\tau^-$)
5) $e^+e^-\to e^+e^-+$ *hadrons*
6) $e^+e^-\to\tau^+\tau^-$
7) $e^+e^-\to Y(1S)$, $Y(2S)$.

The processing of the special runs with the separated beams has shown that after the event selection procedure the contribution from the process 1 is negligible. The contaminations from the processes 2÷6 were estimated using the Monte Carlo simulation. The contribution from the processes 2,3,4 was found to be negligible. The background from the process $e^+e^-\to e^+e^-+hadrons$ was estimated to be 1.5% at $2E=9.4$ GeV and 1 % at $2E=7.4$ GeV. The contamination from the process $e^+e^-\to\tau^+\tau^-$ was 3.5 % and it does not depend on the beam energy. The total background in the nonresonant region was estimated to be 5 % at $2E=9.4$ GeV and it slightly depends on c.m.s. energy. The background from the Y(1S) and Y(2S)-mesons was determined by fitting of the experimental data using procedure described in ref.[15] with 4 free parameters: the masses and the cross-section of the Y-mesons, the energy spread in the machine and the cross section in the continuum. The visible cross-section after background subtraction is shown in Fig.1.

6. RADIATIVE CORRECTIONS AND DETECTION EFFICIENCY

From the visible cross-section after background subtraction the R value is obtained using the expression:

$$R=\frac{\sigma_{vis}}{\varepsilon(1+\delta)}\cdot\frac{1}{\sigma_{\mu\mu}}\ , \qquad (2)$$

where ε is the detection efficiency for the multihadronic events with radiative effects included and $(1+\delta)$ is the radiative correction factor due to QED processes up to order α^3:

$$1+\delta=1+\delta_{soft}+\delta_{hard}+\delta_{vert}+\delta_{vac}\ . \qquad (3)$$

To determine the radiative corrections to the hadronic cross-section and the detection efficiency, events in continuum were generated using the LUND-JETSET 6.3 program

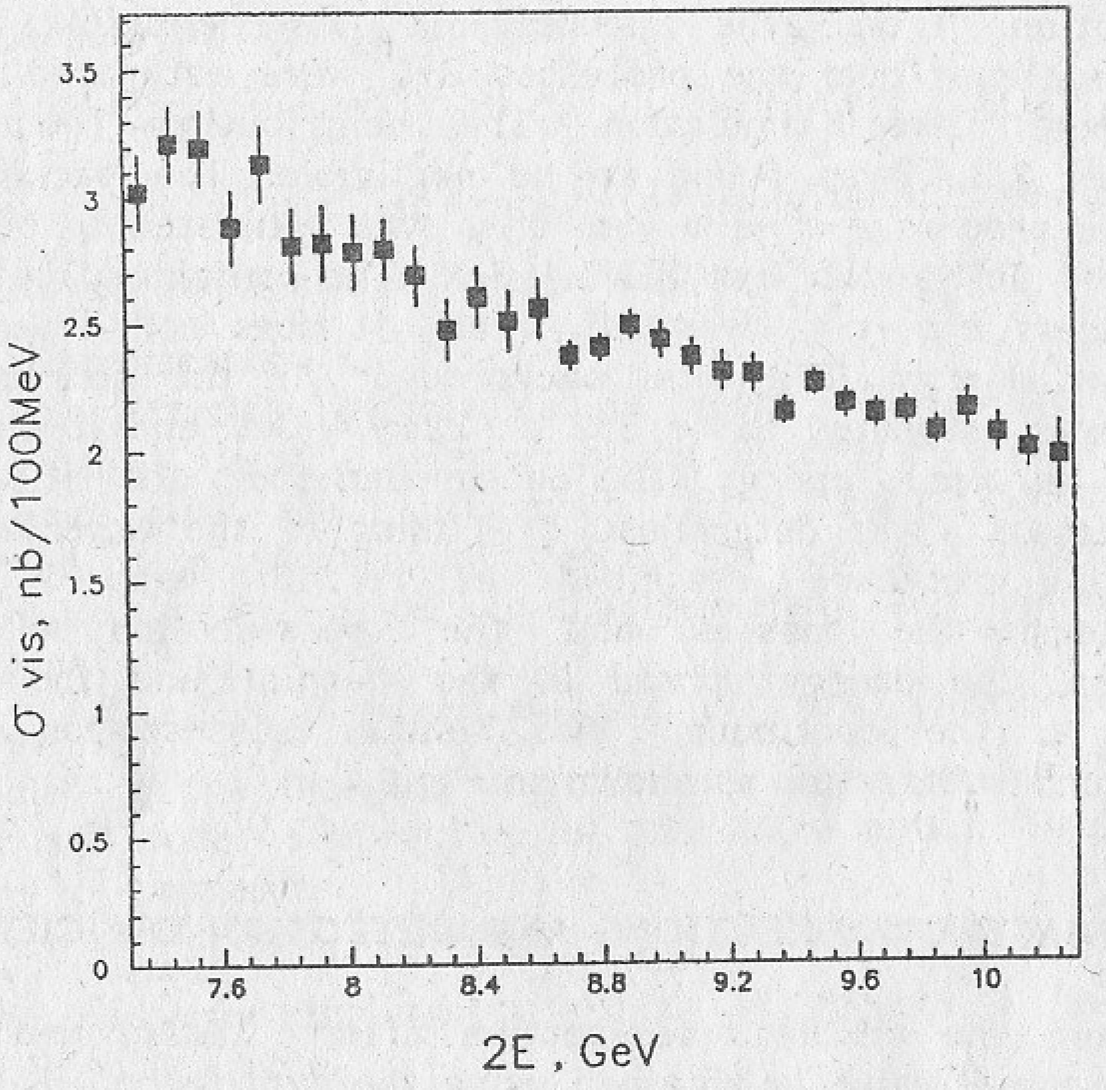

Fig.1. The visible cross-section of $e^+e^- \to$ *hadrons* versus center-of-mass energy.

[16]. In this version the radiative corrections are included according to [17]. For soft photons radiated in initial state the cut-off was applied at 0.01 of the beam energy. For hard photons a cut-off was 0.99 of the beam energy. In this case the value $(1+\delta)=1.234$ at $2E=9.4$ GeV. The value $1+\delta$ depends on cut-off for hard photons but product $\varepsilon\cdot(1+\delta)$ is insensitive to these cuts since the detection efficiency for events with hard photons emitted is small. In our case at $2E=9.4$ GeV, $k_{max} \geq 0.96$, ($E_{cm} \leq 2.0$ GeV) the acceptance is below 1/20. The systematic error in product $\varepsilon\cdot(1+\delta)$ due to uncertainty in the multihadron cross section at low energies and low lying resonances is about 0.1%.

The events generated by the LUND code were passed through a complete detector simulation using the UNIMOD program [18]. The interaction of hadrons in the detector was simulated using the NUCRIN program [19].

There were two important problems with the simulation of the MD-1 detector.

The first one was the efficiency of the track reconstruction in the tracking system. The real response of the proportional chambers differ from ideal case. The real parameters of the chambers were determined using $\mu^+\mu^-$, two-photon and multihadronic events. All kinds of the corrections in the tracking system together change the detection efficiency by (10.5±1.6)% for chosen selection criteria.

The second problem was the simulation hadron interaction in the detector. The simulated hadron range in the shower-range system are somewhat greater than that observed in the experimen. Varying the total interaction cross-section in NUCRIN by as much as 20% gives a small change in the particle ranges. The reason of this is probably too long range of secondary particles. The following rough correction algorithm was used to correct this effect [15]: if the nuclear interaction had occurred during the event simulation, the products of the interaction were ignored with the probability of 15%. The influence of this correction on the detection efficiency was (1.2±0.4)%.

The simulated and observed distributions in some important parameters are shown in Fig.2÷4. The multiplicity, spherisity and momentum distribution data are in a good agreement with the simulation.

The obtained value $\varepsilon\cdot(1+\delta)$ as a function of the c.m.s. energy is shown in Fig.5.

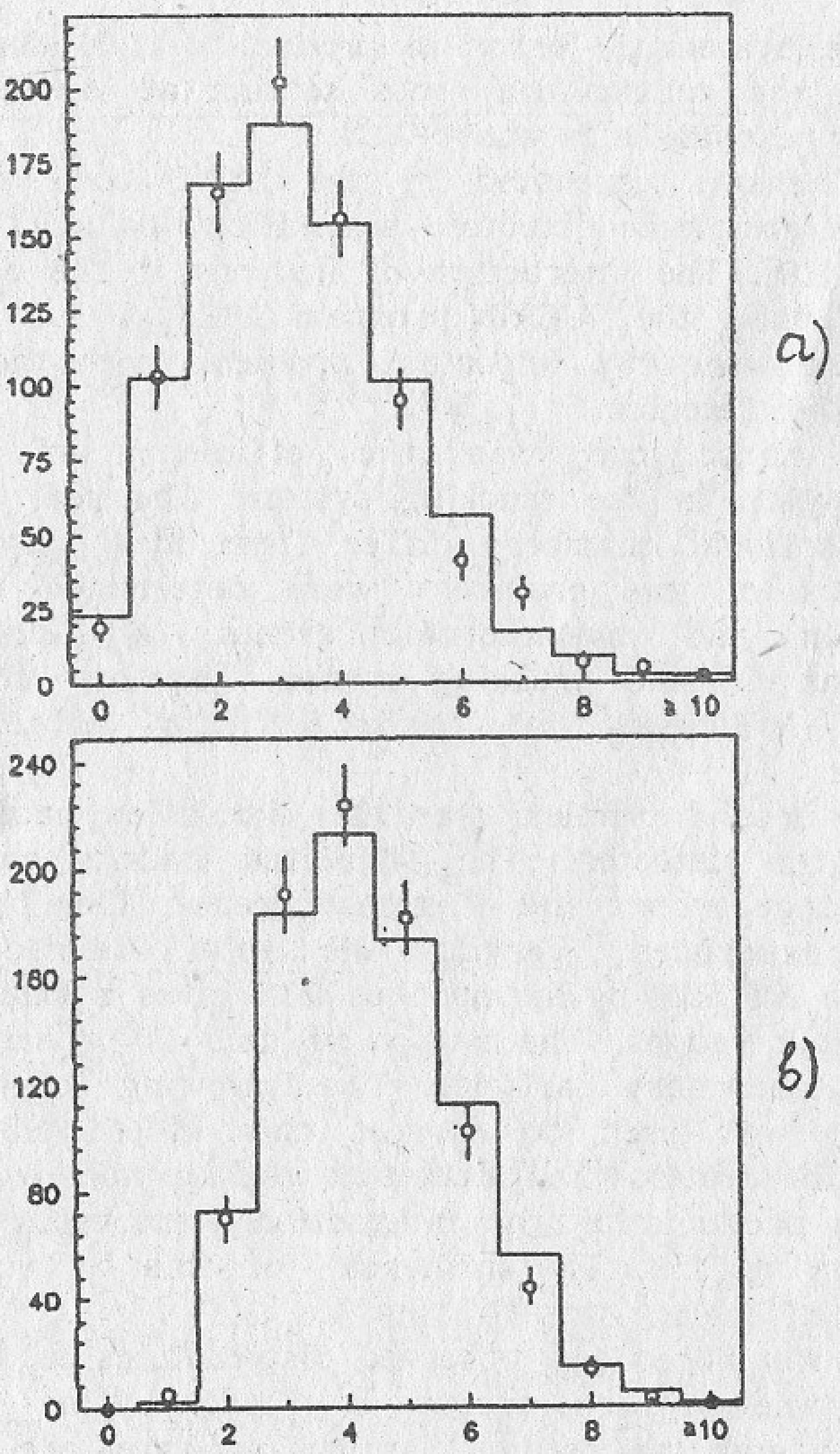

Fig.2. The uncorrected multiplicity distribution at $2E \cong 9.4$GeV (points) compared to the simulation (histogram): (a) – the number of "perfect particles" in the tracking system, (b)-the number of particles in the shower-range system off the mashine plane.

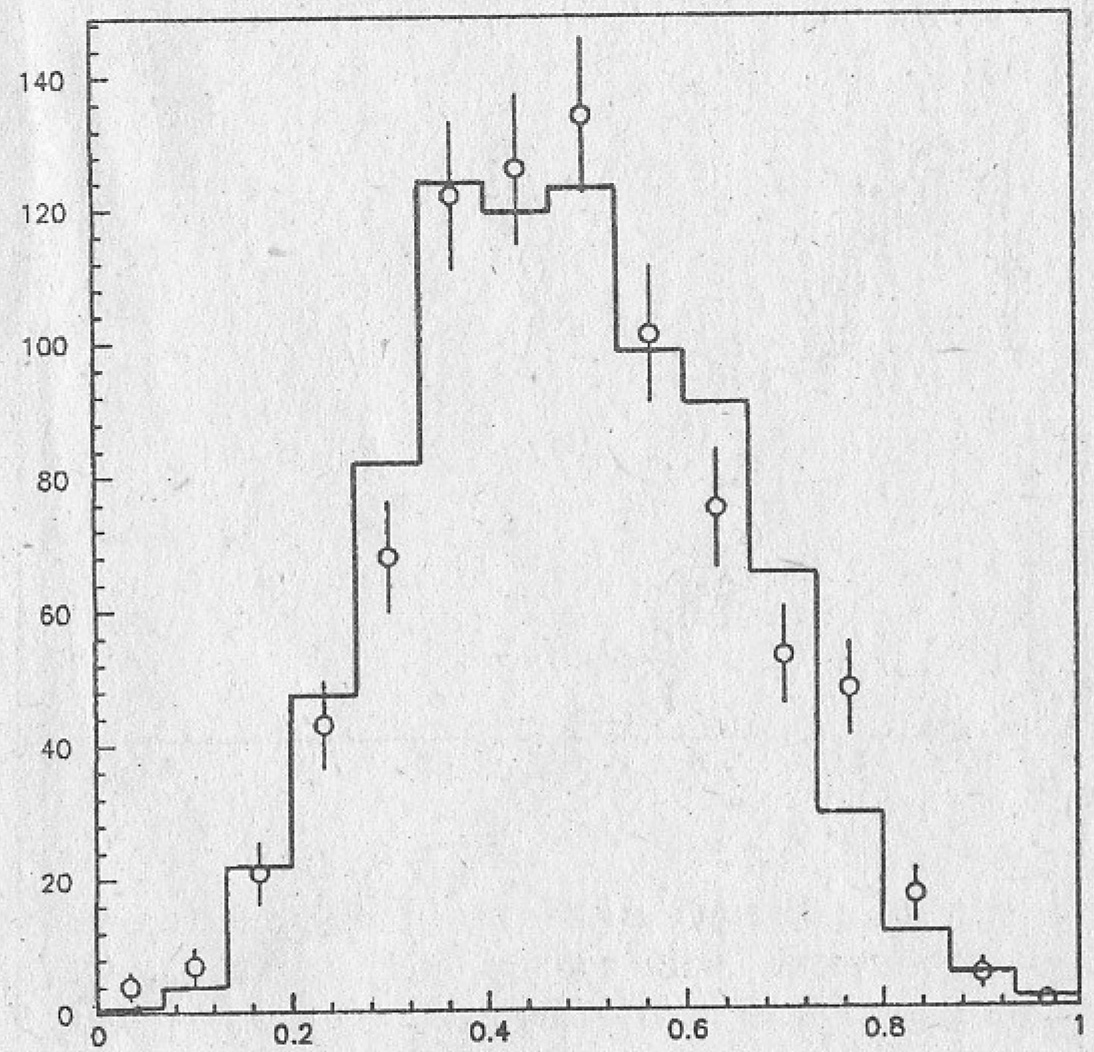

Fig.3. The uncorrected distribution in the sphericity at $2E \cong 9.4$ GeV (points) compared to the simulation.

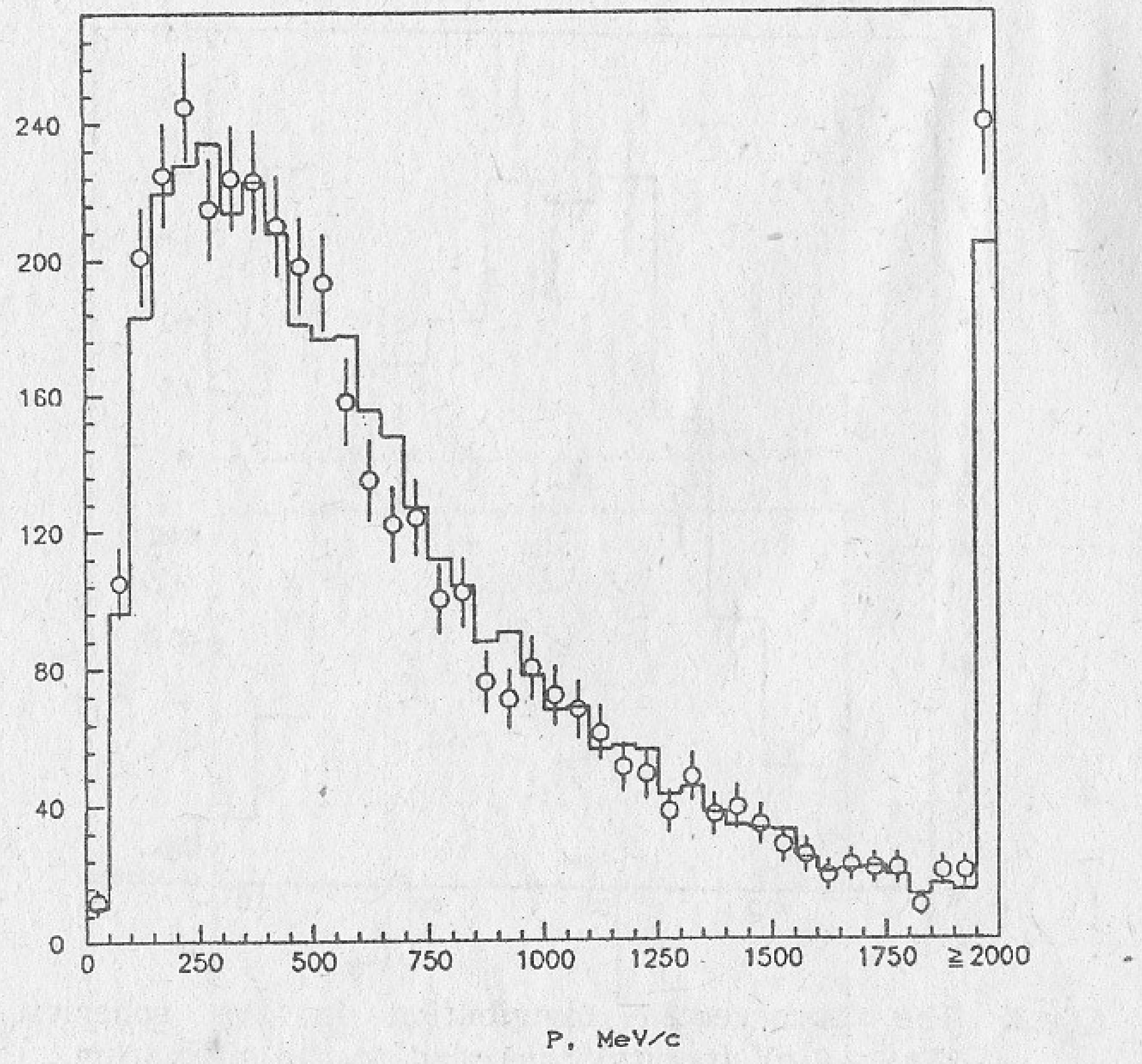

Fig.4. The uncorrected momentum distribution at $2E \cong 9.4$ GeV (points) compared to the simulation.

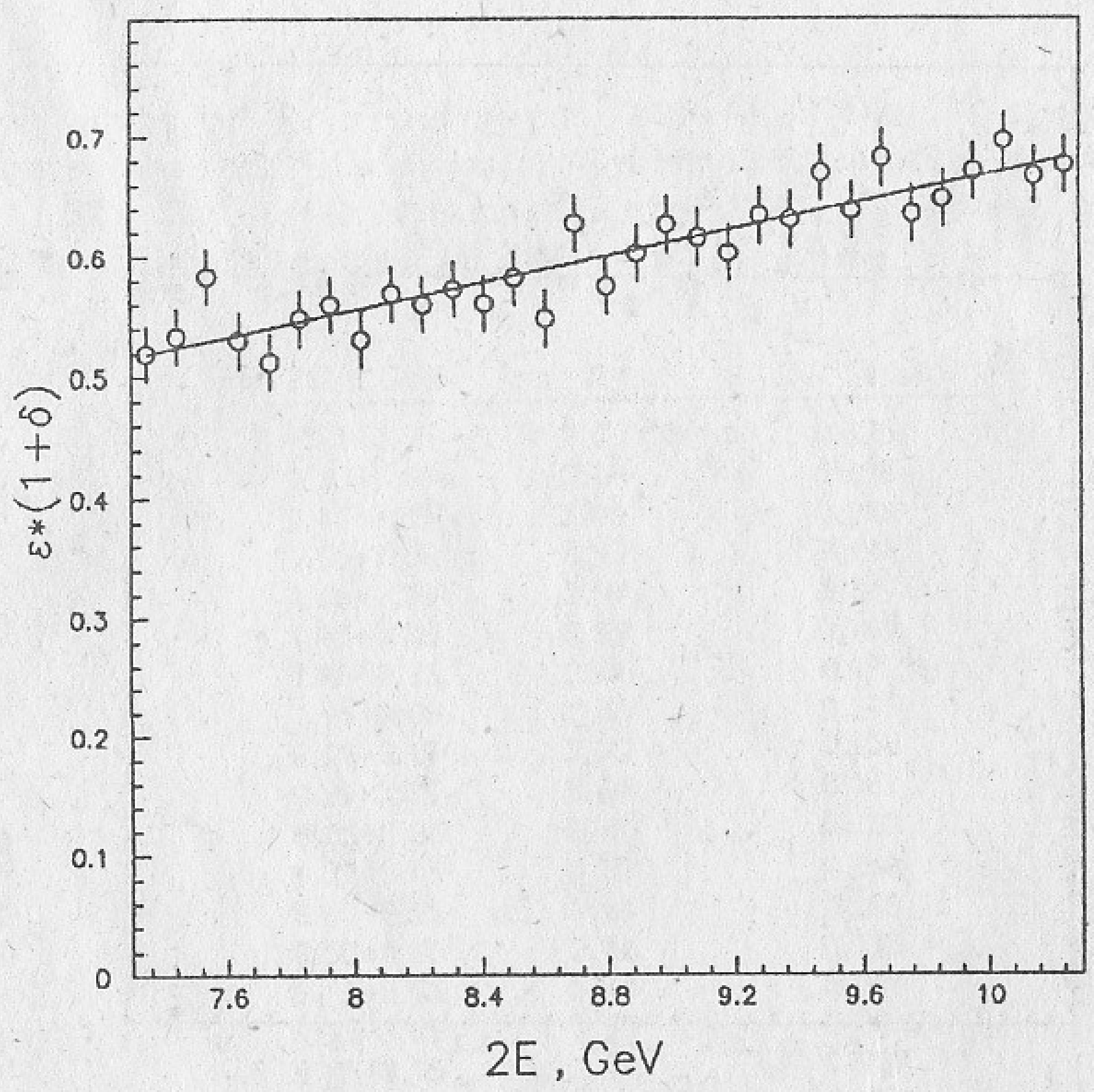

Fig.5. The product $\varepsilon\cdot(1+\delta)$ as a function of the center-of-mass energy. The errors are determined by Monte Carlo statistics. The solid line is a linear fit.

7. DETERMINATION OF R. SYSTEMATIC ERRORS

The R value was determined using eq.2. Its dependence on the c.m.s. energy is shown in Fig.6. The errors shown are statistical only. The data are presented in Table 2. There is no evidence for resonances. The data are fitted wery well by constant (χ^2=28 for 30 degrees of freedom) and we have found $\bar{R}=3.578\pm0.021$.

The systematic error in R is determined by several factors which are described below.

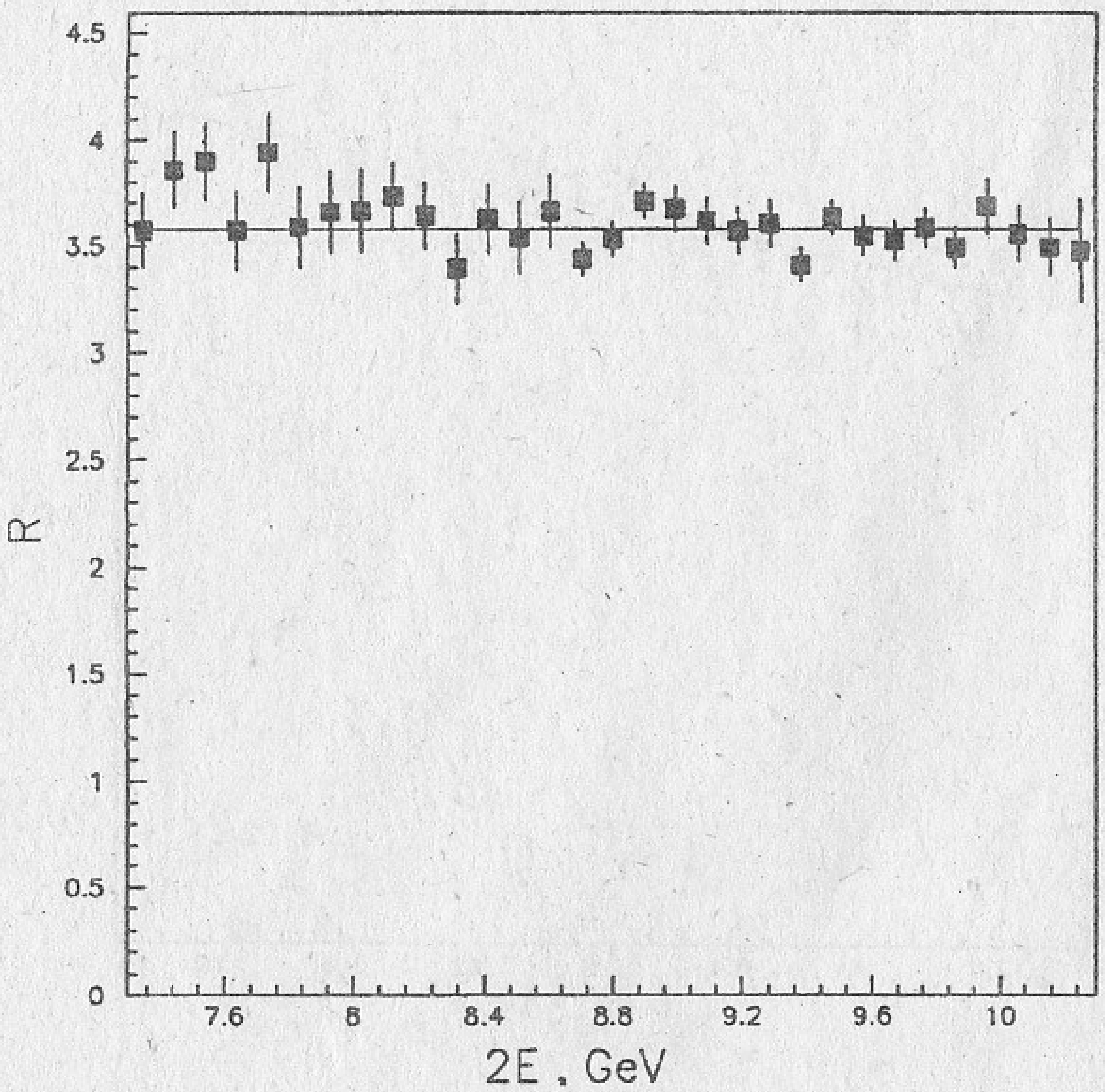

Fig.6. The *R* value dependence on the center-of-mass energy. The errors shown are statistical only. The solid line is the constant fit.

The error due to the detector response (1.7%) was estimated from the variation of chamber efficiencies and nuclear interaction parameters within acceptable limits.

The error arised from hadronization model used was estimated by the following way. The comparison of the data and simulated observed multiplicities (see Fig.2) shows that they are in agreement within the error of 2.0÷3.0%. We adjusted the LUND JETSET 6.2 program parameters so that the observed multiplicity was changed by 2.7% and found the acceptance variation of 2.5%. This value was taken as an estimate of the error due to hadronization model.

Table 2

The values of *R* in the region 7.23÷10.34 GeV. The presented errors are statistical only. Systematic point-to-point error is 1.5%. The total systematic error in each point and for the average value of R is 3.9%.

2E , GeV	*R*	Δ*R* (stat)
7.23+7.35	3.57	0.175
7.35+7.45	3.86	0.178
7.45+7.55	3.89	0.181
7.55+7.65	3.57	0.184
7.65+7.75	3.94	0.187
7.75+7.85	3.59	0.189
7.85+7.95	3.66	0.192
7.95+8.05	3.67	0.195
8.05+8.15	3.73	0.158
8.15+8.25	3.64	0.161
8.25+8.35	3.40	0.163
8.35+8.45	3.63	0.165
8.45+8.55	3.54	0.168
8.55+8.65	3.66	0.170
8.65+8.75	3.44	0.079
8.75+8.85	3.53	0.080
8.85+8.95	3.71	0.081
8.95+9.05	3.67	0.109
9.05+9.15	3.63	0.110
9.15+9.25	3.57	0.112
9.25+9.35	3.60	0.113
9.35+9.45	3.41	0.079
9.45+9.55	3.63	0.080
9.55+9.65	3.55	0.092
9.65÷9.75	3.52	0.093
9.75+9.85	3.58	0.094
9.85+9.95	3.49	0.095
9.95+10.05	3.68	0.130
10.05+10.15	3.56	0.131
10.15+10.25	3.49	0.133
10.25+10.34	3.48	0.239
7.23+10.34	3.578	0.021

(Average value)

(0.4%) was estimated using our measurement of the total cross-section of gamma-gamma into hadrons [20] (in this paper the total cross-section was measured with error about 25%).

The errors due to subtraction of $e^+e^-\to\tau^+\tau^-$ (0.5%) and $e^+e^-\to e^+e^-\gamma$ (0.6 %) processes were determined by Monte Carlo statistics.

We varied most significant cuts to check the stability of the R value: when the detection efficincy was increased by 1.12 times and background by 2.5, due to this variation, the value of R was shifted only by -0.5±0.7%.

The error due to neglecting higher order QED contribion to the radiative corrections was estimated to be 1 %.

The full list of systematic errors is given below:

luminosity measurement	1.9%
detector response	1.7%
model dependence of efficiency	2.5%
Monte Carlo statistics	0.5%
background subtraction;	
$e^+e^-\to e^+e^-+hadrons$	0.4%
$e^+e^-\to\tau^+\tau^-$	0.5%
$e^+e^-\to e^+e^-\gamma$	0.6%
radiative corrections	1.0%

Combining these errors quadratically we obtain the systematic error of 3.9% for the measured R value. Our result for the average R value in the energy region 7.25÷10.34 GeV is

$$\bar{R} = 3.578\pm0.021\pm0.140\ .$$

This value is in a good agreement with *QCD* prediction $R_{QCD}=3.602\pm0.014$ at average scaling parameter $\Lambda=260^{+54}_{-46}$ MeV [31].

The data (Table 2 and fig.6) are also fitted very well by linear fit: $\chi^2=25$ for 29 degrees of freedom. This fit gives the value of slope

$$K=[R(7.2\mathrm{GeV})-R(10.34\mathrm{GeV})]/\bar{R}=0.039\pm0.025(\mathrm{stat}).$$

The systematic uncertainty in this value due to Monte Carlo statistics of efficiency calculation is 0.026. We summed the staistical and systematic errors in quadrature and obtain K< 0.08 at 90% CL.

We devided the energy region 7.25÷10.34 GeV in 6 parts and in the Table 3 and fig.7 our data on R are compared to the previous experiments in the region between 7.0 and 10.5 *GeV*.

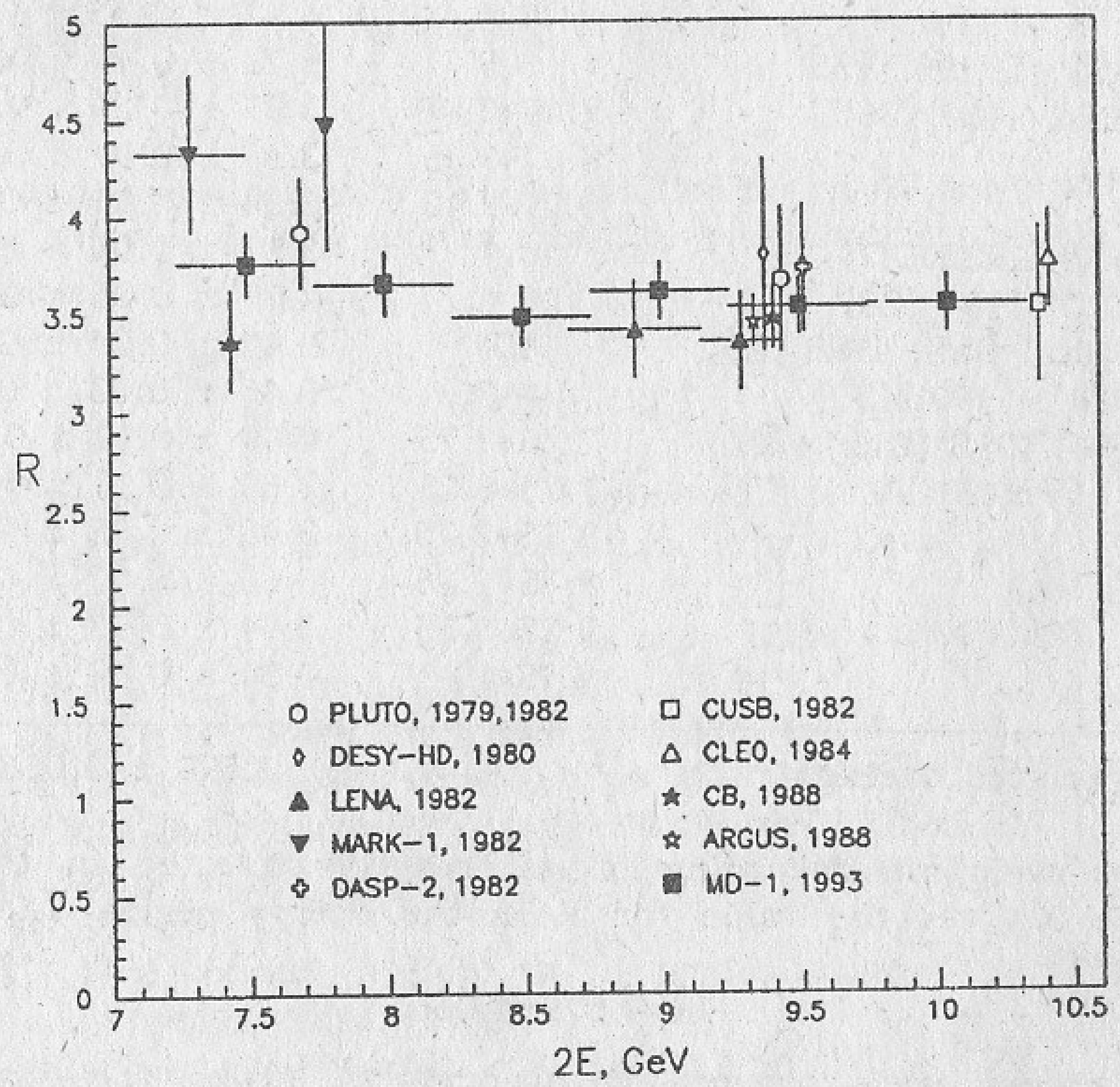

Fig.7. Compilation of the results for R in the energy region between 7.0÷10.5 GeV. The combined errors (statistical and systematic errors sumed in quadrature) are shown.

Table 3

Compilation of R measurement
obtained at center-of-mass energies between 7.0÷10.5 GeV.

Experiment	$2E$, GeV	R
PLUTO, 1979 [21]	7.7	3.92 ± 0.28
DESY - Hidelberg,1980 [22]	9.4	3.80 ± 0.27 ± 0.42
PLUTO, 1982 [23]	9.4	3.67 ± 0.23 ± 0.29
MARK-1, 1982 [24]	7.0÷7.5	4.31 ± 0.04 ± 0.43
	7.8	4.47 ± 0.53 ± 0.45
DASP II, 1982 [25]	9.5	3.73 ± 0.16 ± 0.28
LENA, 1982 [26]	7.40÷7.48	3.37 ± 0.13 ± 0.23
	8.67÷9.15	3.42 ± 0.10 ± 0.23
	9.15÷9.43	3.34 ± 0.09 ± 0.23
CUSB, 1982 [27]	10.4	3.54 ± 0.05 ± 0.40
CLEO, 1984 [28]	10.4	3.77 ± 0.06 ± 0.24
Crystal Ball, 1988 [29]	9.4	3.48 ± 0.04 ± 0.16
ARGUS, 1991 [30]	9.36	3.46 ± 0.03 ± 0.13
MD-1, 1993 [this work]	7.25÷7.75	3.76 ± 0.10 ± 0.15
	7.75÷8.25	3.66 ± 0.10 ± 0.14
	8.25÷8.75	3.49 ± 0.08 ± 0.14
	8.75÷9.25	3.62 ± 0.07 ± 0.14
	9.25÷9.75	3.54 ± 0.07 ± 0.14
	9.75÷10.34	3.54 ± 0.07 ± 0.14
Weigted average		3.579 ± 0.066

The weighted averaging of all results collected in the Table 3 gives the value for $\bar{R}$ in the energy region 7.0÷10.5 GeV:

$$\bar{R}=3.579\pm0.066$$

(all errors were summed in quadrature). Using the formula (1) we obtain $\alpha_s=0.174\pm0.039$ ($2E\cong8.9$ GeV, $n_f=4$, $\beta_4=0.908$). Although the average $\bar{R}$ value has a good accuracy (1.8%) the corresponding error on α_s is about factor 2÷3 worse than it was obtained from study of the direct *QCD* effects [31].

8. SUMMARY

We have performed the detail measurements of the total cross-section of $e^+e^-\to hadrons$ in the c.m.s. energy region between 7.23÷10.34 GeV. The R value was found to be constant in this energy region with the average value of $\bar{R}=3.578\pm0.021\pm0.140$ in agreement with *QCD* predictions and with previous results at similar c.m.s. energies. Our results are the most precise ones (only ARGUS measurement at 9.36 *GeV* has the same systematic error). The R value was not measured before in the energy intervals of 7.8÷8.7 GeV and 9.5÷10.34 GeV.

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The Measurement of R in e^+e^--Annihilation in Center-of Mass Energies between 7.23 and 10.34 GeV

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