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by

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ABSTRACT

Data are presented from five experiments at PETRA and combined where possible. The measured R values show a constant behaviour for the centre of mass energies between 17 and 36.5 GeV, and are compatible with expectations from the quark parton model including five quarks u,d,s,c,b and QCD corrections. The results of two energy scans are reported. The data exclude any $t\bar{t}$ threshold below 36.5 GeV of 2/3 charged t quarks decaying into many hadrons. The search for superheavy sequential leptons and scalar electrons yields negative evidence and lower mass limits are given.

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INTRODUCTION

The reported results were made possible by the efficient operation of the PETRA storage ring, which during its first year of operation supplied a luminosity of about 5500 nb^{-1} for each of the four interaction regions. Each of the experiments JADE, PLUTO, MARK J, and TASSO collected about 2500 multihadronic events; CELLO replaced PLUTO at the beginning of this year.

MEASUREMENTS OF R

The ratio $R = \sigma(e^+e^- \longrightarrow \text{hadrons})/\sigma(e^+e^- \longrightarrow \mu^+\mu^-)$ tests the pointlike nature of quark pair production and counts the number of quarks involved. In order to discriminate hadronic annihilation events from two-photon and beam-gas background, the most important cut - employed by all PETRA experiments [1] - requires that at least 50% of the total centre of mass energy be visible in the detector (25% for the case of only charged particle detection). In addition each event is required to have at least four charged tracks and $\tau^+\tau^-$ topologies are explicitely removed from the event sample with four tracks. These cuts lead to a clean sample of hadronic annihilation events losing only a few good events. The missing fraction mainly depends on how well the detectors cover the full solid angle. All quoted cross sections are corrected for acceptance and radiative effects which in all cases include hadronic vacuum polarization of about 5%. In Fig. 1a the measured R values are given for five PETRA experiments in the energy range from 12 to 36.5 GeV and a few measured points at lower energies [2] for comparison. The most obvious feature is that from 17 GeV onwards the R values seem to be constant and compatible with what one expects for five quarks plus QCD corrections.

According to the quark-parton model the expected R value is obtained by adding the squares of the quark charges Q_i and multiplying this sum by QCD corrections up to second order. In the version of Dine and Sapirstein [3] R reads:

$$R = 3\sum_{i=1}^{N_f} Q_i^2 \left\{ 1 + \frac{\alpha_s(s)}{\pi} + (\ 1.98 - 0.115\ N_f\ )\ (\ \frac{\alpha_s(s)}{\pi}\ )^2 \right\} \qquad (1)$$

where $\alpha_s(s) = \frac{12\pi}{(33-2N_f)\ln(s/\Lambda^2)}$, $\sqrt{s}$ = centre of mass energy.

N_f is the number of flavours and Λ the QCD parameter. In Fig. 1b the PETRA measurements are averaged for each energy point and compared with the result of equ. (1) for Λ values of 1 GeV (upper curve) and 0.2 GeV (lower curve). The agreement is good but one has to keep in mind that in addition to the statistical errors shown each experiment quotes a possible normalization error of about 10% which does not necessarily cancel by combining various experiments. Averaging all R values above 20 GeV yields:

JADE	MARK J	PLUTO	TASSO	ALL 4 EXPERIM.
R_i = 3.84+0.10	4.17+0.10	3.82+0.14	4.0+0.13	R_o = 3.97+0.06

From the variation of the four values R_i one can estimate the error for the individual measurement $\Delta = \sqrt{\Sigma (R_o - R_i)^2/3} = 0.16$ (or 4%) which corresponds roughly to the quoted statistical errors. Therefore, if 10% normalization errors are hidden in the data they have to work at least partly in the same direction for the various experiments. With this note of caution in mind one can now compare the above average R_o for all experiments with what one expects from equ. (1) at 30 GeV:

R = 3.92+0.06 for α_s = 0.20+0.04 (or Λ = 0.5 +0.5/-0.3 GeV)

SEARCH FOR $t\bar{t}$ THRESHOLDS

The normalized cross section R suggests the absence of any $t\bar{t}$ threshold of 2/3 charged t quarks below 36.5 GeV. However, the most sensitive test is to look at the event topology. As the energy increases, the events are more and more collimated into jets. This can be seen from the monotonic decrease of the sphericity [4] (Fig. 2) which roughly measures the average of the square of the jet cone half opening angle. Pair-produced t quarks would lead to an isotropic particle distribution for a sizable fraction of events and consequently to an increase of the average sphericity by 0.08 (dashed line in Fig. 2). One step further is to look at the sphericity and aplanarity [4] simultaneously which is done in the triangle plot of Fig. 3a for events above 35 GeV. Two-jet events cluster in the left-hand corner and gluon bremsstrahlung spreads some of the events along a band of low aplanarity. However, the Monte-Carlo simulation in Fig. 3c shows that $t\bar{t}$ production populates the triangle rather evenly. Therefore, selecting only events with an aplanarity larger than 0.15, one expects for the energy range in Fig. 3a (Fig. 3b) a total of 5 (1) events in the case of five quarks u,d,s,c,b and 57 (9) events in the case of an additional t quark. The observed number of 2 (0) events clearly demonstrates the absence of any $t\bar{t}$ threshold up to the highest energies obtained. If one combines the TASSO measurement in Fig. 3 with nearly identical measurements of JADE and MARK J, one finds that the $t\bar{t}$ threshold is excluded with 12 s.d. at 35.3 GeV and with 5 s.d. at 36.5 GeV. This statement holds if the t quark decays via the sequence $t \to b \to c \to s$ into many hadrons, as suggested by the Kobayashi-Maskawa generalized Cabibbo matrix [5]. Another consequence of this scheme is that the t decay is a rich source of leptons. In Fig. 4 the fraction of events with a muon of at least 2 GeV momentum is given and the data clearly favour the yield from c and b quarks only.

A 1/3 charged quark does not fit into the above decay scheme. However, if it were to decay into many hadrons, it would have been seen at 30 and 35 GeV with the experimental technique just discussed. Therefore, contributions from any additional 1/3 charged quarks are quite unlikely but cannot be excluded for quark masses below 10 GeV.

ENERGY SCAN

The search for a $t\bar{t}$ threshold can be extended beyond the highest available energy by looking for $t\bar{t}$ bound states below threshold. For this purpose, scans in 20 MeV steps have been performed in the energy ranges 29.9 to 31.5 and 35.0 to 35.6 GeV (Fig. 5). A gaussian curve, corrected for radiative effects [6], was fitted at each energy point $\sqrt{s}$ and the integral of this cross section curve is given by $\int \sigma \, d\sqrt{s} = 6\pi^2 B_h \Gamma_{ee}/s$ where B_h is the branching ratio into hadrons and Γ_{ee} the electronic width. For $\Gamma_{ee} = 5$ KeV and an energy resolution of 20 MeV one expects an increase in R of about 7. From the non-observation of any significant peak one obtains upper limits for $B_h \cdot \Gamma_{ee}$ of 0.7 and 0.4 KeV in the above energy ranges respectively. The scan is presently continued from 35 GeV downwards.

SEARCH FOR SUPERHEAVY SEQUENTIAL LEPTONS

When searching for final states including neutrinos, which escape detection, one has to employ a cut on the visible energy which is quite different from the case of selecting purely hadronic final states. In fact, the selection is guided by model calculations [7] in order to maximize the acceptance for sequential leptons heavier than the τ and to minimize the acceptance for hadronic annihilation and two-photon events. The detailed cuts depend on the specific properties of the detectors and are given in the following table.

EXPER.	SELECTION CRITERIA FOR $e^+e^- \longrightarrow L^+L^-$	M_L (GeV)
PLUTO	single μ recoiling against many hadrons $E_{vis} > 3$ GeV; $\lvert \vec{P}_{miss} \rvert > 2.5$ GeV; Thrust < 0.95	>14.5
MARK J	single μ recoiling against many hadrons $10\% < E_{vis}/\sqrt{s} < 50\%$; $(\Sigma \vec{P})(-\vec{\mu})/E_{vis} < 0.8$	>15
TASSO	single charged particle A recoiling against many hadrons $\Sigma \lvert \vec{P}_i \rvert \geqslant 8$ GeV, i = ch.tr. $\geqslant 5$; $\measuredangle(\vec{P}_i, \vec{A}) \geqslant 90^\circ$	>13
JADE	$11 < E_{vis} < 32$ GeV for $\sqrt{s} = 35$ GeV $\lvert \cos \theta_T \rvert < 0.75$ w.r.t. e^+ axis $(\text{plane}(\vec{T}, \vec{e^+}), \text{plane}(\Sigma \vec{P}_{OTS}, \vec{e^+})) > 45^\circ$ where T = thrust and OTS = opposite thrust side	>17

No events have been found by the four experiments and lower mass limits for superheavy sequential leptons are given in the right-hand column of the table.

SEARCH FOR SCALAR ELECTRONS

Supersymmetric theories require all particles to have partners with spin different by half a unit [8]. Therefore, the partner of the electron would be a scalar electron which can be pair-produced in e^+e^- annihilation and which decays into an electron and a neutrino-like particle. The signature of such a process would be two electrons, which do not form a plane containing the beam axis, and no additional signal in the detector. PLUTO and JADE searched for these final states by demanding an acoplanarity angle of more than

$15^o/10^o$ and electron energies of at least 20%/30% of the beam energy. Because no candidates were observed at centre of mass energies of 31 GeV for PLUTO and 35 GeV for JADE, the lower mass limits for scalar electrons are 13 and 16 GeV respectively.

CONCLUSIONS

Measurements of the normalized cross section R show a constant behaviour over the energy range from 17 to 36.5 GeV. They agree well with the quark-parton model with five quarks plus QCD corrections but are fairly insensitive to variations of the strong coupling constant α_s. Additional processes contributing to the multihadronic final state are not completely excluded due to possible normalization errors of 10% but they are certainly limited to less than half a unit of R.

Lower mass limits for top quarks, superheavy sequential leptons, and scalar electrons are 18, 17, and 16 GeV respectively.

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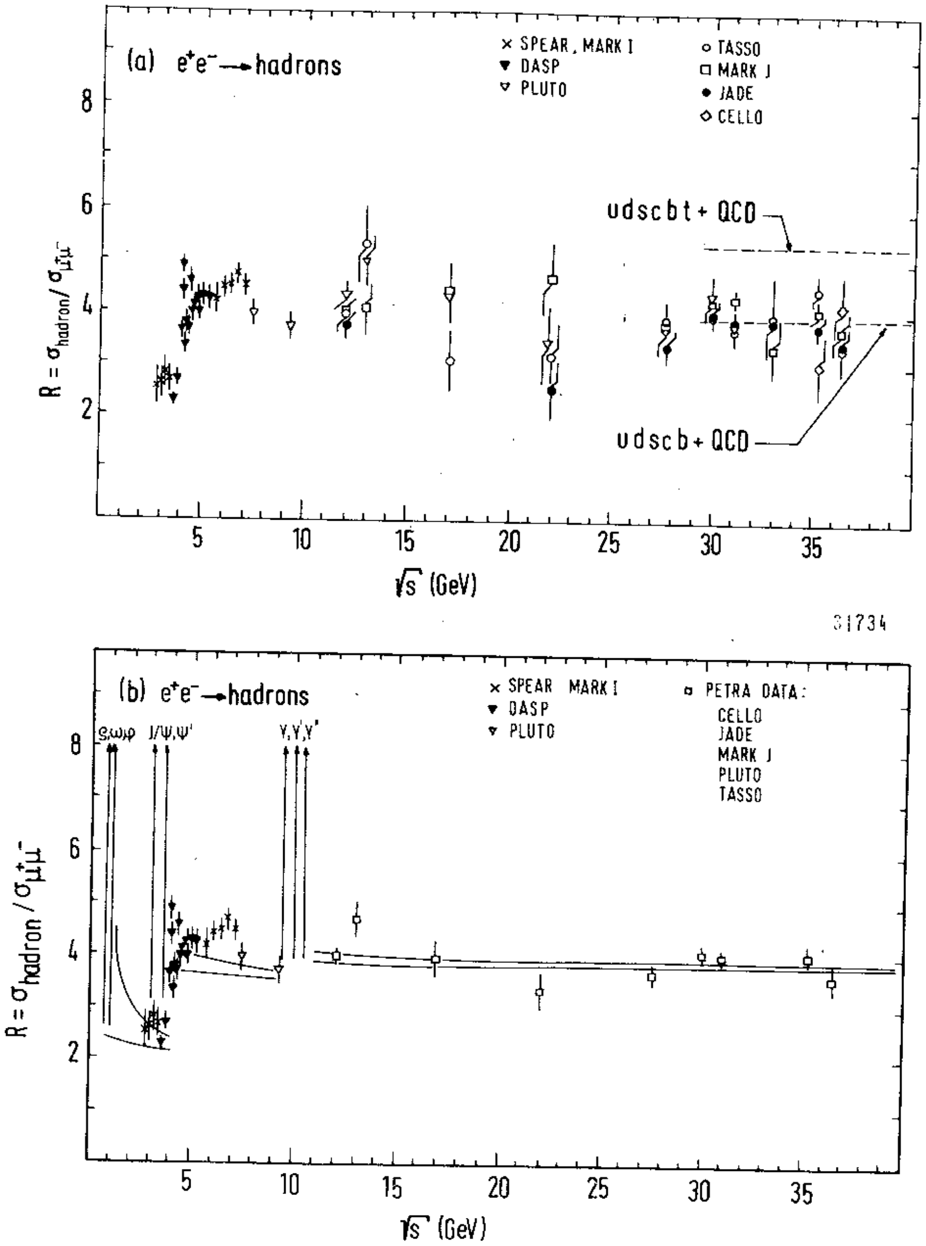

Fig. 1: Ratio of hadronic to $\mu^+\mu^-$ cross section as function of centre of mass energy $\sqrt{s}$. Measurements at PETRA are shown (a) separate and (b) combined. The curves are calculated from equ. (1) with Λ = 1.0/0.2 GeV for upper/lower line.

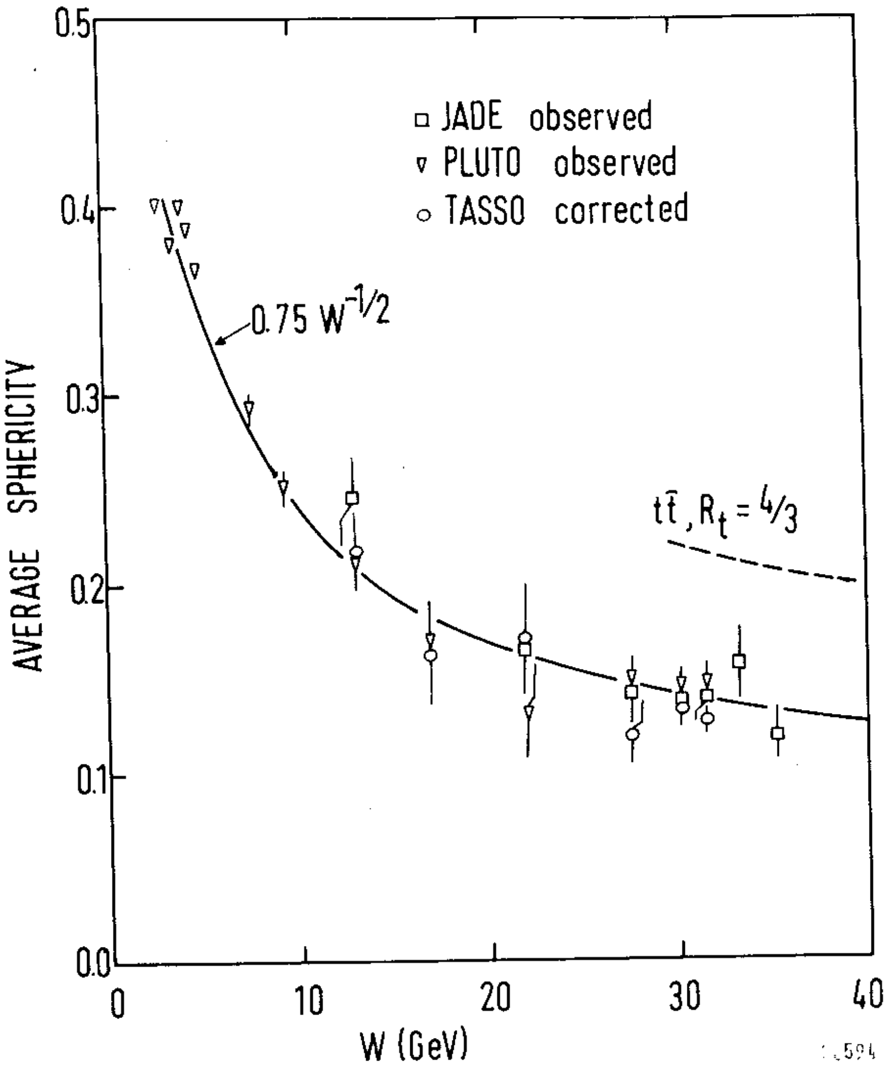

Fig. 2: Average shpericity versus centre of mass energy W.

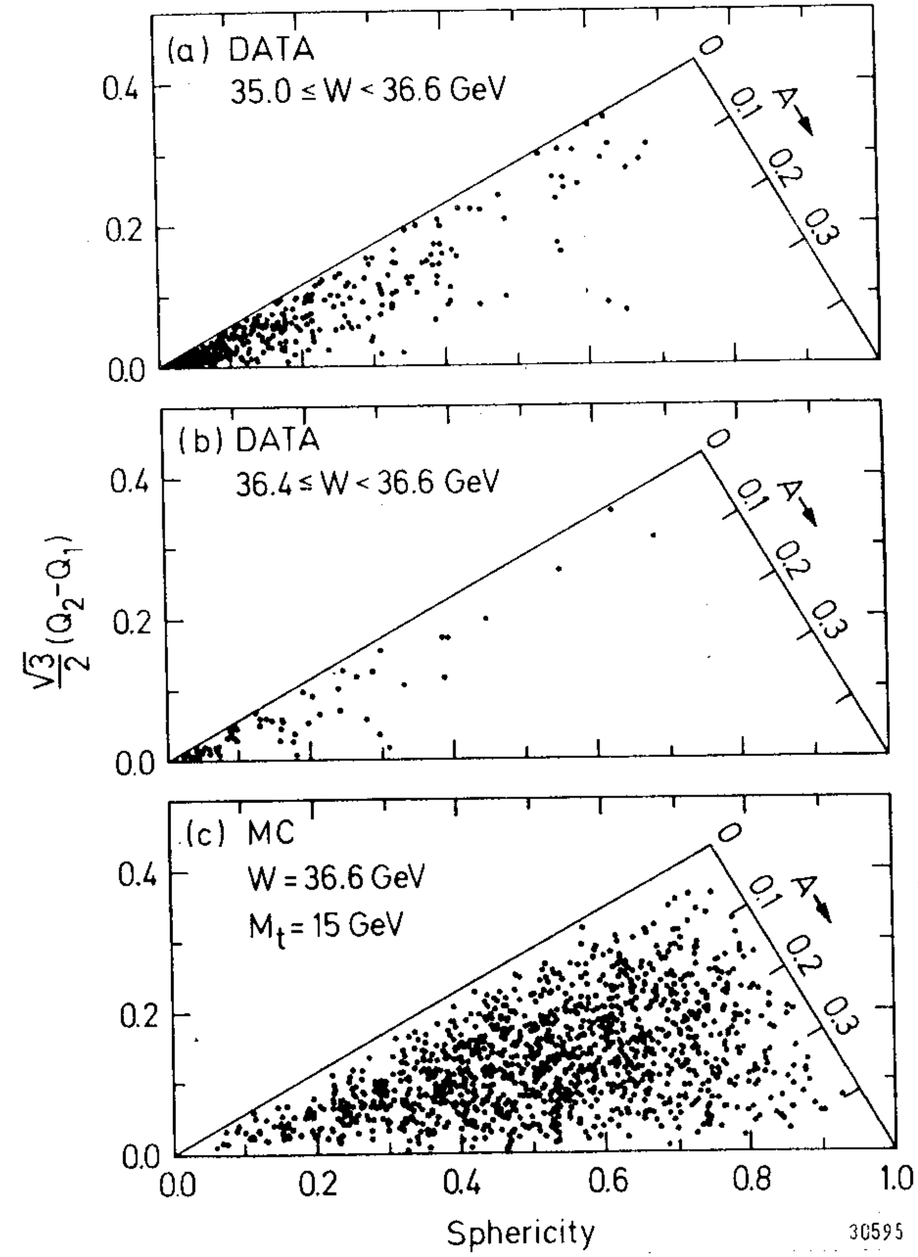

Fig. 3: Distribution of events as a function of sphericity and aplanarity A. (a) and (b) show TASSO data for two energy regions. (c) is a Monte-Carlo simulation for $e^+e^- \longrightarrow t\bar{t} \longrightarrow$ hadrons.

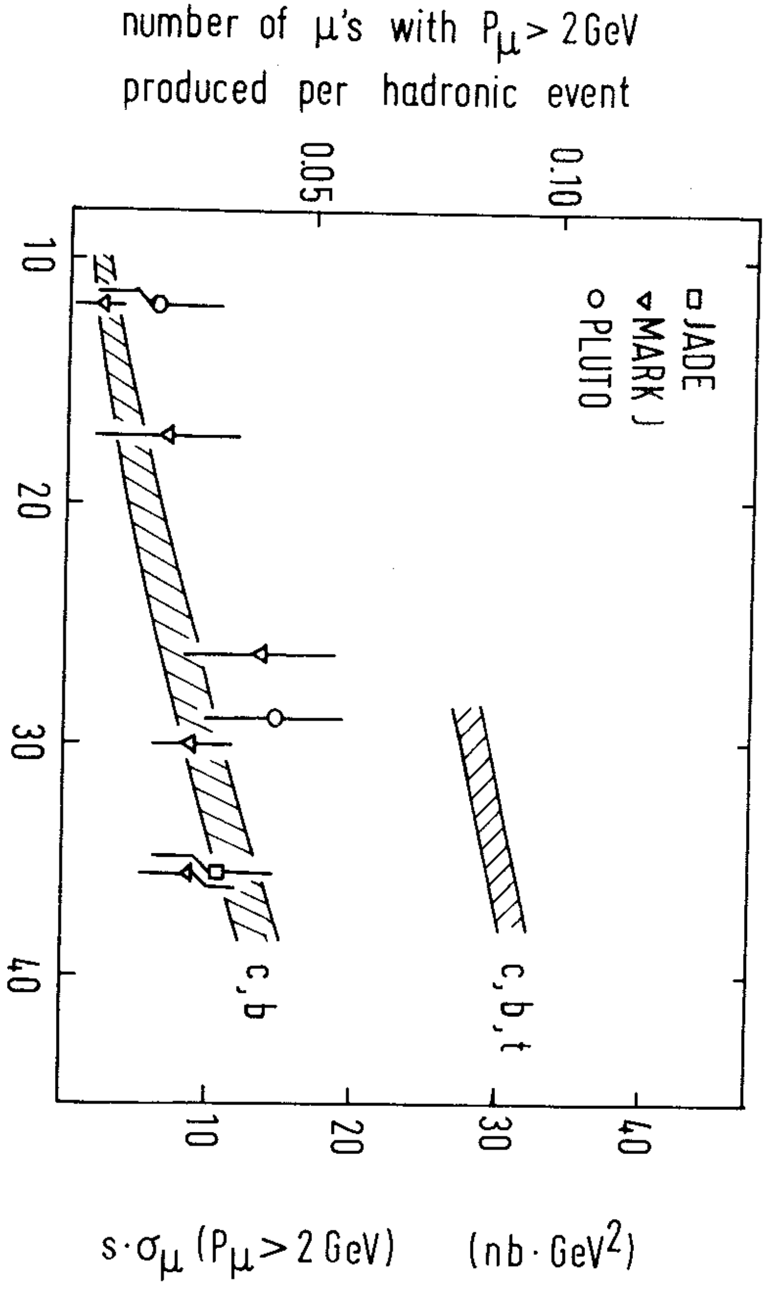

Fig .4: Inclusive production of muons with momentum greater than 2 GeV. The predictions correspond to Feynman-Field/constant fragmentation functions at the lower/upper edge of the bands.

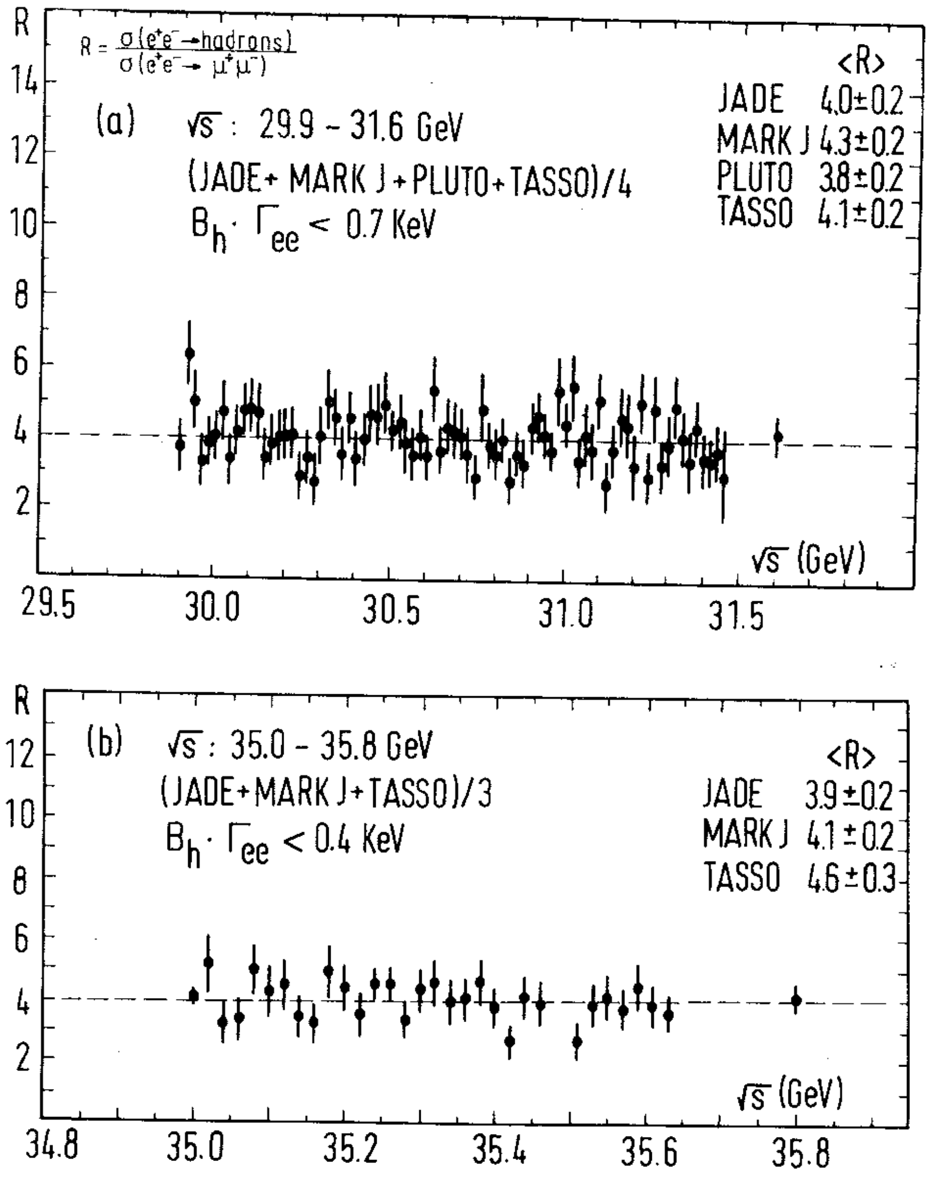

Fig. 5: Energy scan of (a) four and (b) three experiments combined. The upper limits for $B_h \cdot \Gamma_{ee}$ are obtained as described in the text.