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A MEASUREMENT OF  $\sigma_{\text{tot}}$  ( $e^+e^- \rightarrow \text{HADRONS}$ )  
FOR C.M. ENERGIES BETWEEN 12.0 AND 36.7 GeV

by

*TASSO Collaboration*

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A Measurement of  $\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})$  for C.M. Energies Between 12.0 and 36.7 GeV

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## Abstract

The ratio  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma_{\mu\mu}$  was measured between 12.0 and 36.7 GeV c.m. energy  $W$  with a precision of typically  $\pm 5.2\%$ .  $R$  is found to be constant with an average of  $R = 4.01 \pm 0.03$  (stat.)  $\pm 0.20$  (syst.) for  $W \geq 14$  GeV. Quarks are found to be pointlike, 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,  $\sigma_{tot}$ , for  $e^+e^-$  annihilation into hadrons is a quantity of fundamental importance. In the quark parton model  $\sigma_{tot}$  measures the sum of the squares of the quark charges  $e_q$ ,

$$R \equiv \sigma_{tot} / \sigma_{\mu\mu} = 3 \sum_q e_q^2 \quad (1)$$

where  $\sigma_{\mu\mu} = \frac{4\pi\alpha^2}{3s}$  ( $s$  = 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 special 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 IASSO 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  $\sim 42\,000\text{ nb}^{-1}$ . The detector as well as the data taking and analysis procedures have been described elsewhere<sup>1,2</sup>.

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  $\theta$  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 ( $W \geq 27$  GeV),
2. to suppress the contribution from  $\tau$  pair production at  $W < 15$  GeV ( $W > 15$  GeV) events with 3 charged tracks in one hemisphere w.r.t. 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  $\tau$  mass (assuming pion masses for the observed particles),
3. for  $W \leq 14$  GeV, tracks were required in both hemispheres defined with respect to the beam axis, 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  $|z_v| < 6$  cm,
5. the momentum sum  $\sum p \equiv \sum |p_i|$  of the particle momenta had to be  $\sum p > 0.265 W$ .

These cuts discriminated against beam gas scattering (3-5),  $\tau$  pair production (1,2), Bhabha scattering and  $\mu$  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,  $\sigma_{tot}$ , at a 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  $\mathcal{L}$ :

$$\sigma_{tot}(W) = \frac{1}{\mathcal{L}} (N_{meas} - N_{bg}) / A \quad (2)$$

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

$$A = \int d\vec{k} f(\vec{k}) a(\vec{k}, W) \frac{\sigma_{tot}(W')}{\sigma_{tot}(W)} \quad (3)$$

where  $\vec{k}$  is the momentum vector of the photon emitted in the initial state.  $f(\vec{k})$  describes the spectrum of photons emitted in the initial state with

momentum vector  $\vec{k}$  plus all other radiative corrections,  $W'$  is the c.m. energy of the hadronic system produced,  $W' = \sqrt{W^2 - 2W|\vec{k}|}$ ,  $a(\vec{k}, W')$  is the acceptance for a hadronic system with c.m. energy  $W'$  and momentum  $-\vec{k}$ .

In the following we discuss the determination of the quantities that enter the expression for  $\sigma_{tot}$  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  $0.5 \pm 0.5\%$  at  $W \leq 15$  GeV and negligible at higher energies. The contribution of  $\tau$  pair production was determined by a Monte Carlo method to be  $1.5 \pm 1.5\%$  at  $W \leq 15$  GeV and  $1.2 \pm 1.2\%$  at  $W \geq 15$  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<sup>4</sup>. The background from  $\gamma\gamma$  processes was found to be  $1.6 \pm 0.8\%$  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  $\epsilon$  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,  $\epsilon = 98.4 \pm 1.0\%$ ,  $98.1 \pm 1.0\%$  and  $98.1 \pm 1.0\%$ , 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<sup>5</sup> according to  $e^+e^- \rightarrow q\bar{q}$  and  $e^+e^- \rightarrow q\bar{q}$  using Field-Feynman fragmentation functions<sup>6</sup>. Baryon production was

also included<sup>7</sup>). The fragmentation parameters<sup>\*)</sup> were determined previously by this experiment and were found to describe well the charged particle data<sup>8</sup>. 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.

The radiative effects were calculated with a computer program by Berends and Kleiss<sup>10</sup> 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  $\sigma_{tot}$  and the description of the final states at  $W' \ll W$ .  $\sigma_{tot}$  enters in the calculation of the hadronic vacuum polarization (which increases the observable cross section by ~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,  $|\sum p_z|$ , is particularly large for these events. Using the sphericity tensor, the event plane and the angle  $\Theta_n$  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  $|\sum p_z|/\sum p$  for events with  $|\cos\Theta_n| < 0.2$ . The Monte Carlo

\*) Due to our acceptance criteria the contribution to R from the two-body channels  $e^+e^- \rightarrow \pi^+\pi^-, K^+K^-$  and  $p\bar{p}$  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<sup>9</sup>. 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  $\tau$  pair production, events were discarded which had hits in the muon chambers following the calorimeter. The R value for pair production of charged hadrons ( $\pi, K, p$ ) was found to be  $R < 0.03$  (95% C.L.).

prediction is shown by the solid curve which is seen to describe the data well. The shaded area show the Monte Carlo prediction for "radiative" events having  $W' < 0.8 W$ ; they are seen to be important at large  $|\sum p_z|/\sum p$ . For  $|\cos\theta_n| < 0.2$  and  $|\sum p_z|/\sum p > 0.2$  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 which were not included can be expected<sup>(11)</sup> to change  $A$  by  $(0.15)^2 \approx 2 \%$ . We estimate that the uncertainties in the radiative corrections contribute in total a  $\pm 2.5 \%$  systematic error to  $\sigma_{\text{tot}}$ .

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,  $n_{\text{CH}}$ , and the normalized momentum sum over all observed particles,  $\sum p/W$ . The Monte Carlo predictions are indicated by the curves. The single particle distributions for  $\cos\theta$  and  $p_{xy}$  are reproduced. The distributions of  $n_{\text{CH}}$  (Fig. 1d) and  $\sum p/W$  (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  $n_{\text{CH}}$  distribution is broader than the observed one. The prediction for  $\sum p/W$  describes the data well except for a small shift ( $\sim 0.015$ ) 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<sup>(8)</sup>; (b) by varying the cuts in the multiplicity and in  $\sum p$  separately and together. Varying these cuts within reasonable limits had only a small effect on the value of  $\sigma_{\text{tot}}$ : e.g. at  $W = 34$  GeV increasing the  $p_{xy}$  cut from 0.1 GeV/c to 0.25 GeV/c changed  $\sigma_{\text{tot}}$  by less than 0.8 %, or raising the multiplicity cut continuously from 5 to 11 charged particles changed  $\sigma_{\text{tot}}$  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 ( $\mathcal{L}_F$ ) centered at scattering angles around  $2^\circ$ , and independently in the central detector ( $\mathcal{L}_C$ ) accepting  $|\cos\theta| < 0.8$ . Radiative corrections were applied<sup>(9)</sup>. The statistical errors are in both cases negligible. The systematic error for  $\mathcal{L}_F$  varied between 4.0 and 6.0 %. The accuracy of  $\mathcal{L}_C$  depended mainly on the efficiencies for triggering and track reconstruction. 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 and Table 1 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 and Table 1 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 systematic 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.)  $\pm 0.20$  (syst.) for  $W \geq 14$  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  $\beta$  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 % C.L. 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<sup>2,12</sup>). 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<sup>13</sup>.

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 beams,

$$\sigma_M(\text{GeV}) = 2.2 \cdot 10^{-5} W^2 (\text{GeV}^2)$$

or  $\sigma_M = 27$  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 structure is observed. Proceeding as in Ref. 14 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

$$\int \text{od}W < 31 \text{ nb MeV} \quad (95 \% \text{ C.L.})$$

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

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

It excludes the presence of a vector ground state  $\overline{00}$  for charge 2/3 quarks for which  $\Gamma_{ee} = 5$  keV and  $B_h \approx 0.7$  is expected<sup>15</sup> while a charge 1/3  $\overline{00}$  state cannot be ruled out ( $\Gamma_{ee} \approx 1.3$  keV,  $B_h \approx 0.7$ ). However, by combining with the results from other PEIRA experiments<sup>11,16</sup> one obtains  $\Gamma_{ee} B_h < 0.7$  keV<sup>12</sup> which excludes also the latter possibility.

As a result of the preceding 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 pointlike, provided the quark-parton picture is correct. In terms of the quark magnetic form factor  $G_M$ , R is given by<sup>17</sup>

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

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  $W \geq 14$  GeV yield  $M > 186$  GeV (95 % C.L.). 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 % C.L.). The result can also be expressed in terms of cut-off parameters,  $G_M(s) = (1 \mp s/(s - A_{\pm}^2))$ , which yields  $A_{+} \equiv M > 186$  GeV and  $A_{-} > 363$  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

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

where  $C_2 = 1.39$  in the  $\overline{MS}$  scheme<sup>18</sup>. R can also receive contributions from the weak neutral current, for which evidence was found recently in the reaction  $e^+e^- \rightarrow \mu^+\mu^-$ <sup>9,19</sup>. The expression for  $\sigma_{\text{tot}}$  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<sup>20</sup>

$$R = \frac{1}{\sigma_{\mu\mu}} \sum_q \left\{ \left[ 1 + C_1 \frac{\alpha_s}{\pi} + C_2 \left( \frac{\alpha_s}{\pi} \right)^2 \right] \sigma_{VV}^q + \left[ 1 + C_1^a \frac{\alpha_s}{\pi} + C_2^a \left( \frac{\alpha_s}{\pi} \right)^2 \right] \sigma_{AA}^q \right\} \quad (5)$$

where

$$C_1^V = \frac{4\pi}{3} \left( \frac{\pi}{28} - \frac{3+\beta_q}{4} \left( \frac{\pi}{2} - \frac{3}{4\pi} \right) \right), \beta_q = (1 - 4m_q^2/s)^{1/2}, C_1^A = 1, C_2^V = 1, C_2^A = 1.39^* \quad (6)$$

$$\sigma_{VV}^q = \frac{1}{2} (3\beta - \beta^3) \left\{ \frac{4\pi\alpha}{s} e_q^2 - \frac{4G_F\alpha}{\sqrt{2}} e_q^3 g_V^e g_V^q \text{Re}(X) + \frac{G_F^2}{2\pi} (g_V^e{}^2 + g_A^e{}^2) g_V^q{}^2 s |X|^2 \right\}$$

$$\sigma_{AA}^q = \beta^3 \frac{G_F^2}{4\pi} (g_V^e{}^2 + g_A^e{}^2) g_A^q{}^2 s |X|^2, \quad G_F \text{ is the Fermi coupling constant}$$

$$X = \frac{M_Z^2}{M_Z^2 - s + i M_Z \Gamma_Z}, \quad M_Z = 74.6 \text{ GeV}/\sin 2\theta_W$$

$$g_V^{e,q} = \mp \frac{1}{2} - 2Qs \sin^2 \theta_W$$

$$g_A^{e,q} = \mp \frac{1}{2}$$

the minus sign 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  $\alpha_s$  was described in terms of the QCD parameter  $\Lambda$  using the second order formula<sup>13</sup>.

\* 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  $C_2^q$  a numerical evaluation is given in Ref. 20. 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.

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

$$\chi^2 = (F - 1)^2 / \sigma_{\text{norm}}^2 + \sum (R_i F - R(\alpha_S, \sin^2\theta_W))^2 / \sigma_i^2 \quad (7)$$

where the  $R_i$  are the measured R values with errors  $\sigma_i$  (not including  $\sigma_{\text{norm}}$ ), and F is the overall normalization factor treated as a free parameter. Since  $\alpha_S$  is found to be small, F and  $\alpha_S$  are completely correlated. The fit was therefore done with F set to  $F = 1$  yielding  $\alpha_S(s = 1000 \text{ GeV}^2) = 0.18 \pm 0.03 \pm 0.14$ ,  $\sin^2\theta_W = 0.40 \pm 0.16 \pm 0.02$  with a  $\chi^2 = 12.1$  for 11 d.o.f. The second errors given reflect the error due to  $\sigma_{\text{norm}}$ . 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<sup>21)</sup> the fit gave  $\alpha_S(s = 1000 \text{ GeV}^2) = 0.24 \pm 0.05 \pm 0.13$ . Measurements of three-jet production in  $e^+e^-$  annihilation yielded in first order QCD  $\alpha_S \approx 0.17$ <sup>8,22)</sup> for  $s \approx 1000 \text{ GeV}^2$ . Second order corrections give either  $\alpha_S = 0.17$ <sup>23)</sup> or  $\alpha_S = 0.12$ <sup>24)</sup>. Assuming  $\alpha_S = 0.17$  (0.12) the fit yielded  $F = 1.00 \pm 0.04$  ( $1.01 \pm 0.04$ ) and  $\sin^2\theta_W = 0.40 \pm 0.15 \pm 0.02$  ( $0.39 \pm 0.14 \pm 0.02$ ). Our results on  $\alpha_S$  and  $\sin^2\theta_W$  are consistent with those obtained in Refs. 25, 26.

If we take the weak coupling constants  $g_a, g_V$  as measured in lepton scattering<sup>27)</sup> (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  $M_Z$ ,  $M_Z > 45 \text{ GeV}$  (95 % C.L.). 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  $\pm 5.2$  % 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  $W \geq 14 \text{ GeV}$ . 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  $< 31 \text{ nb}$  which excludes the presence of the expected vector ground state of toponium. Quarks have been found to be pointlike, the mass parameter describing a possible quark formfactor being larger than 186 GeV. The R values of  $W \geq 14 \text{ GeV}$  were compared with QCD and with the predictions of the Weinberg-Salam theory for the weak neutral current. The fit yielded for  $\alpha_S$  evaluated at  $s = 1000 \text{ GeV}^2$ ,  $\alpha_S = 0.18 \pm 0.03 \pm 0.14$  and  $\sin^2\theta_W = 0.40 \pm 0.16 \pm 0.02$ .

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Table 1 Values for  $R = \sigma_{\text{tot}}/\sigma_{\mu\mu}$  as a function of c.m. energy for runperiod I (1979,1980) and runperiod II (1981). The errors quoted include the statistical as well as the point-to-point systematic error. An overall uncertainty of  $\pm 4.5\%$  has to be added. The relative uncertainty between the two runperiods is  $\pm 2\%$ .

Runperiod I

W[GeV]	$\bar{W}$ [GeV]	$\mathcal{L}$ [nb <sup>-1</sup> ]	number of events	R
12.0	12.0	96.3	186	$3.80 \pm 0.28$
27.4 - 27.7	27.5	337.0	141	$3.91 \pm 0.32$
29.9 - 30.5	30.1	1309.4	460	$3.94 \pm 0.18$
30.5 - 31.5	31.1	1317.6	407	$3.66 \pm 0.18$
32.5 - 33.5	33.2	762.6	262	$4.48 \pm 0.28$
33.5 - 34.5	34.0	1422.2	410	$4.09 \pm 0.20$
34.5 - 35.5	35.0	2224.4	592	$4.03 \pm 0.17$
35.5 - 36.7	36.1	2213.3	543	$3.93 \pm 0.17$

Runperiod II

14.0	14.0	1631.0	2704	$4.14 \pm 0.30$
22.0	22.0	2785.4	1889	$3.89 \pm 0.17$
25.0	25.0	454.9	231	$3.72 \pm 0.38$
33.0	33.0	817.9	220	$3.73 \pm 0.27$
34.0	34.0	11143.0	3269	$4.13 \pm 0.13$
35.0	35.0	15786.5	4532	$4.22 \pm 0.09$

Table 2 Values for  $R = \sigma_{\text{tot}}/\sigma_{\mu\mu}$  in the energy range  $33.0 \leq W \leq 36.7$  GeV

W	R	$\pm \Delta R$	W	R	$\pm \Delta R$	W	R	$\pm \Delta R$
33.00	3.19	0.63	34.30	5.86	1.54	35.50	2.61	1.21
33.06	3.75	0.72	34.32	4.02	1.30	35.52	5.07	1.56
33.08	3.28	1.07	34.34	5.95	1.68	35.54	3.49	1.20
33.10	2.71	1.06	34.36	3.65	1.33	35.56	4.24	1.02
33.12	5.19	1.47	34.38	3.11	1.07	35.58	5.58	1.14
33.14	4.04	1.25	34.40	3.86	1.25	35.60	2.80	0.92
33.16	6.60	1.58	34.42	3.46	1.07	35.62	4.02	1.10
33.18	2.82	1.10	34.44	6.39	1.62	35.68	5.00	1.61
33.20	5.52	1.78	34.46	5.95	1.82	35.70	0.88	0.69
33.28	4.78	1.41	34.48	3.10	1.21	35.72	2.35	0.71
33.30	4.57	1.41	34.50	2.93	1.24	35.74	3.47	0.87
33.32	5.85	1.65	34.52	3.42	1.17	35.76	5.64	1.22
33.34	6.15	1.73	34.54	4.00	1.18	35.78	0.99	0.77
33.36	3.12	1.44	34.56	1.60	0.76	35.80	4.50	0.75
33.38	5.68	1.83	34.58	3.07	0.85	35.82	2.37	1.23
33.40	5.30	1.50	34.60	3.95	1.17	35.84	5.23	1.89
33.42	2.31	1.08	34.62	3.92	1.27	35.86	4.52	1.54
33.44	4.50	1.39	34.64	4.44	1.26	35.88	2.11	0.99
33.46	5.31	1.50	34.66	3.83	1.48	35.90	3.39	1.74
33.48	4.06	1.39	34.68	5.76	2.07	35.92	3.78	1.58
33.50	6.54	1.78	34.70	5.47	1.54	35.94	3.68	1.54
33.52	3.59	1.23	34.72	3.91	1.34	35.96	2.40	1.02
33.54	3.68	1.34	34.74	6.60	1.67	35.98	3.19	1.65
33.56	3.33	1.30	34.76	3.39	1.23	36.00	5.50	1.87
33.58	5.83	1.64	34.78	4.27	1.38	36.02	2.04	1.07
33.60	3.47	1.26	34.80	3.90	1.15	36.04	4.77	1.40
33.62	3.18	1.64	34.82	2.29	0.90	36.06	3.09	1.20
33.64	4.21	1.44	34.84	2.08	0.89	36.08	2.78	1.09
33.66	8.36	1.94	34.86	4.67	1.44	36.10	3.06	1.29
33.68	1.40	0.86	34.88	3.22	1.25	36.12	5.37	1.65
33.70	3.63	1.32	34.90	4.87	1.57	36.14	5.00	1.61
33.72	3.24	1.26	34.92	3.90	1.79	36.16	4.54	1.47
33.74	3.16	1.23	34.94	5.29	1.44	36.18	4.93	1.52
33.76	4.79	1.48	34.96	3.93	1.34	36.20	2.90	1.23
33.78	5.33	1.04	34.98	1.76	0.93	36.22	2.54	1.08
33.80	3.65	0.70	35.00	4.12	0.46	36.24	2.09	1.10
33.82	4.74	0.87	35.02	4.04	1.07	36.26	6.51	1.77
33.84	4.58	0.98	35.04	4.85	1.11	36.28	4.46	1.52
33.86	2.74	0.82	35.06	1.58	0.97	36.30	2.98	1.38
33.88	5.25	0.72	35.08	3.31	1.29	36.32	3.25	1.37
33.90	4.54	1.01	35.10	4.64	1.68	36.34	2.26	1.05
33.92	5.18	1.10	35.12	2.38	1.11	36.36	2.59	1.35
33.94	2.79	0.91	35.14	1.55	0.95	36.38	7.32	2.14
33.96	5.82	1.97	35.16	2.24	1.05	36.42	4.82	1.64
34.00	3.77	0.89	35.18	4.52	1.54	36.44	6.06	1.71
34.02	4.11	1.40	35.20	8.47	2.29	36.46	3.70	0.63
34.04	3.92	1.34	35.22	5.68	1.83	36.48	2.90	1.22
34.06	4.08	1.21	35.24	4.68	1.02	36.50	4.32	1.40
34.08	2.56	1.01	35.26	4.36	1.12	36.52	3.56	1.38
34.10	4.28	1.26	35.28	3.29	1.20	36.54	4.72	1.52
34.12	3.28	1.13	35.30	3.03	1.11	36.56	1.60	0.98
34.14	3.57	1.30	35.32	3.47	1.19	36.58	3.03	1.28
34.16	6.90	2.02	35.34	3.66	1.25	36.60	2.23	1.16
34.18	3.82	1.31	35.36	5.44	1.60	36.62	2.17	1.13
34.20	5.14	1.23	35.38	6.47	1.70	36.64	2.79	1.45
34.22	2.78	1.18	35.40	4.16	1.28	36.66	3.31	0.62
34.24	2.14	1.12	35.42	3.58	1.16	36.68	5.05	1.95
34.26	4.34	1.34	35.44	5.30	1.50	36.70	2.36	1.23
34.28	1.76	0.93	35.46	3.25	1.37			

## Figure Captions

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.

Fig. 2 a) The ratio  $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma_{\mu\mu}$  where  $\sigma_{\mu\mu} = 4\pi\alpha^2/3s$ . The data from other experiments were taken from Refs. 17, 26, 28, 29.

- b) The same as in (a) with the measurements from this experiment, from runperiod I (1979 & 1980) (●), and runperiod II (1981) (■). The errors shown include the statistical and the point-to-point systematic uncertainty but not the overall normalization uncertainty of  $\pm 4.5\%$  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  $\alpha_s(s = 1000 \text{ GeV}^2) = 0.18$  and  $\sin^2\theta_W = 0.23$ .

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

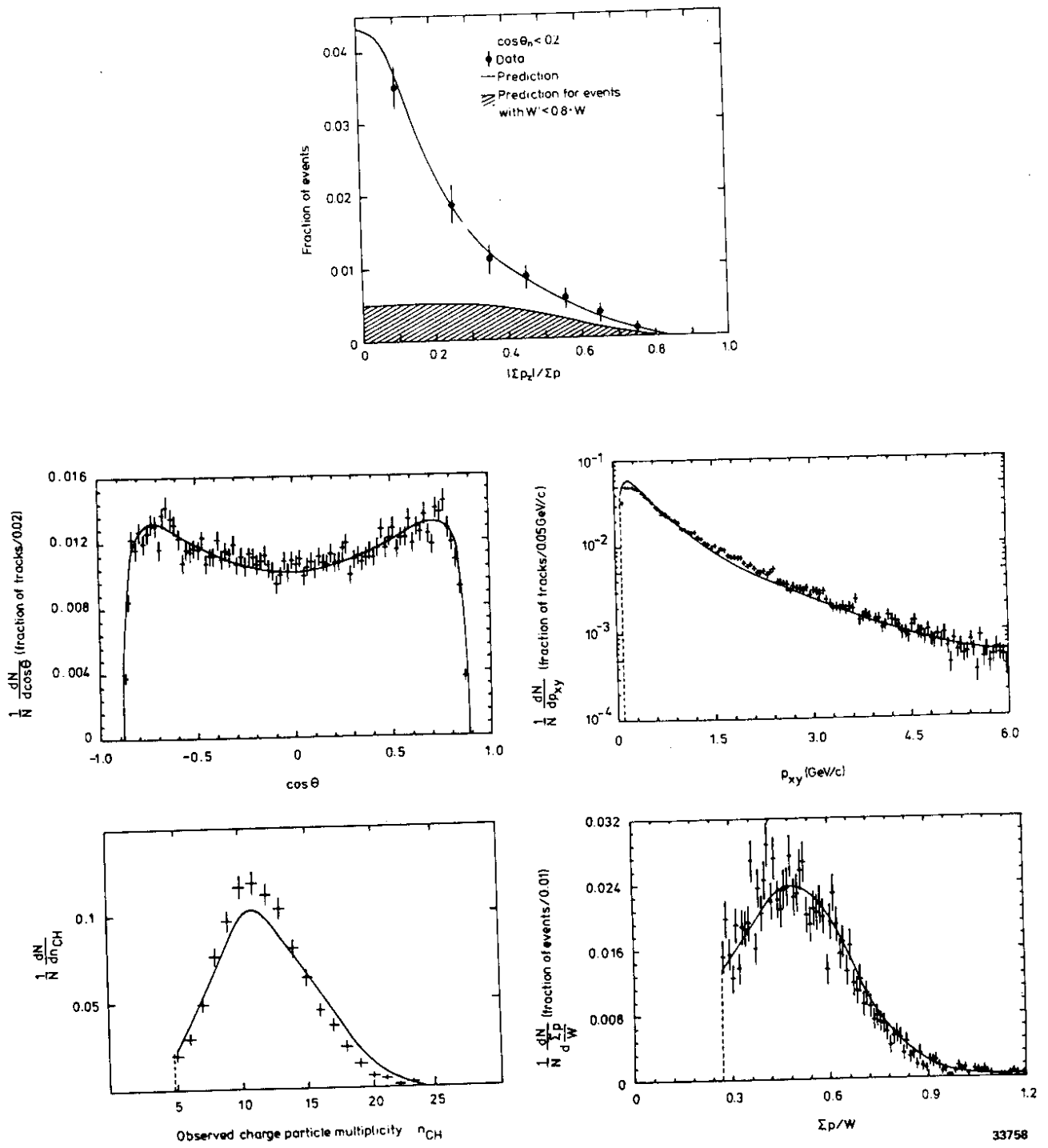
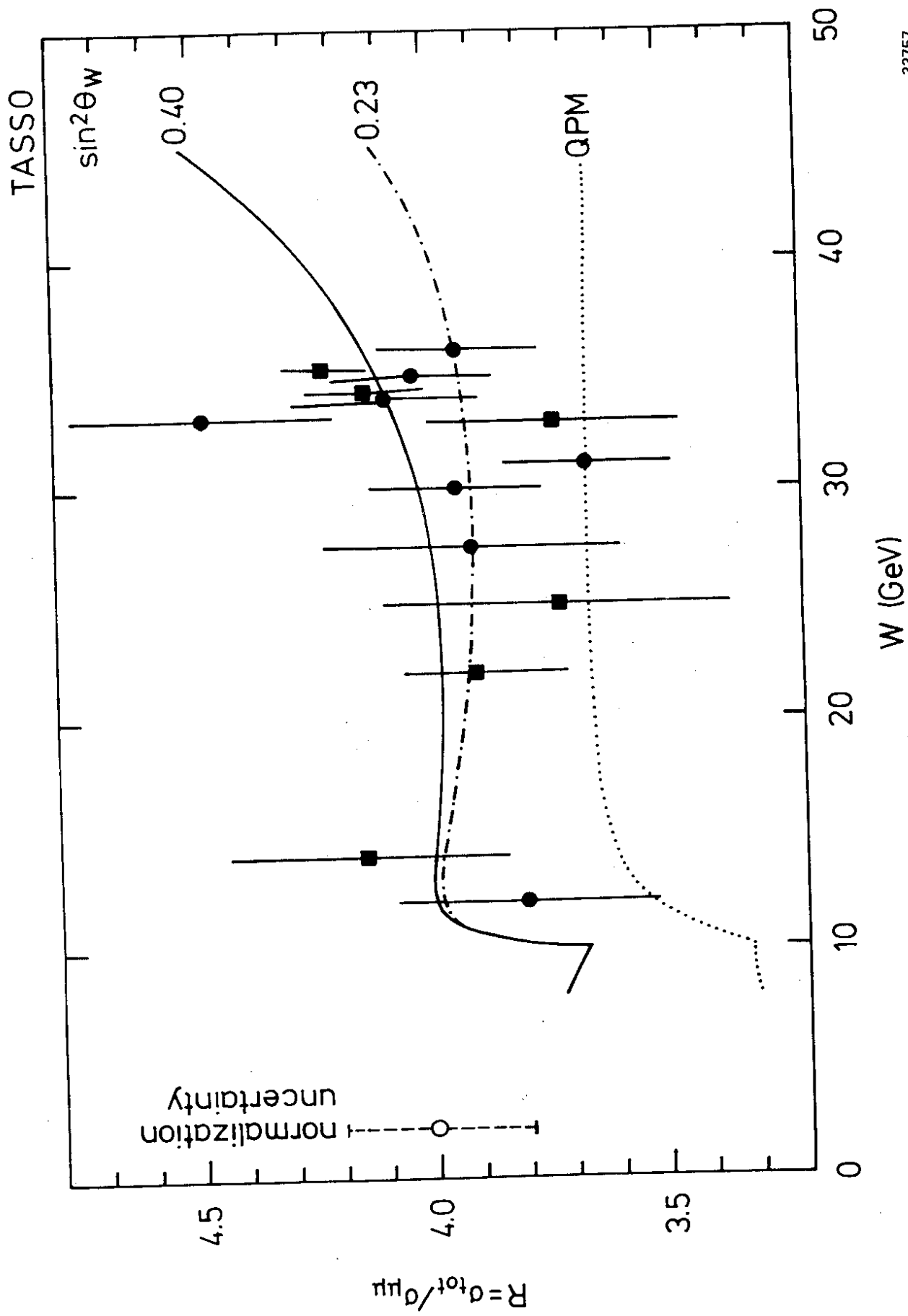


Fig. 1





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Fig. 2b

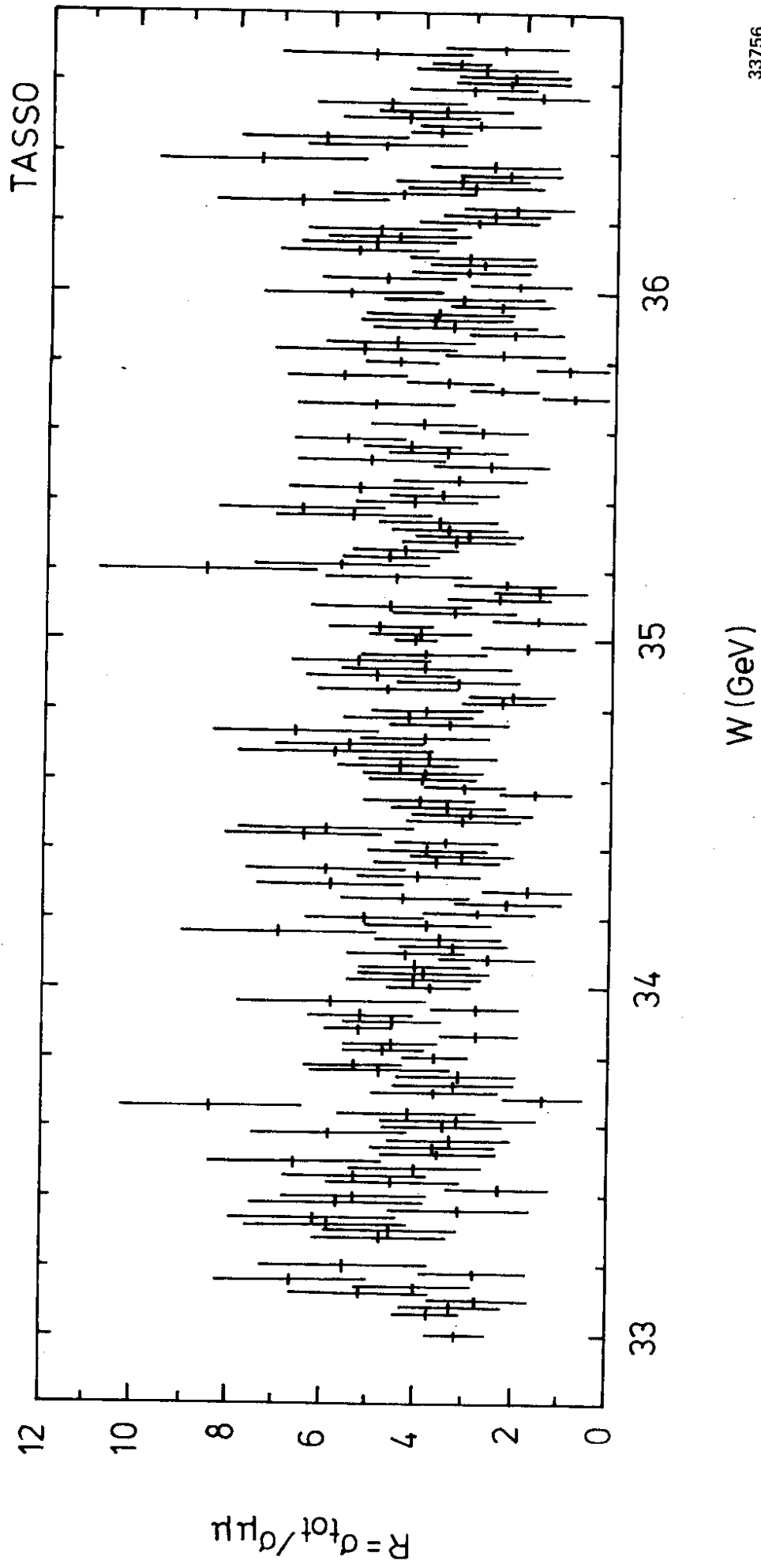


Fig. 3