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e^+e^- Annihilation at High Energies and Search for the t-Quark Continuum Contribution

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Abstract. Measurements of R, sphericity and thrust are presented for c.m. energies between 12 and 31.6 GeV. A possible contribution of a $t\bar{t}$ continuum can be ruled out for c.m. energies between 16 and 31 GeV.

If quarks occur in weak isospin doublets, a sixth quark t, with charge 2/3 is required to complement the known u, d, s, c, and b quarks. Predictions for the mass of the t quark cover a wide range of values [1]; the majority are within the reach of present PETRA energies, namely 10 to 15 GeV. The presence of a new

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quark Q will manifest itself in e^+e^- annihilation as one or more narrow vector states in the total hadronic cross section σ_t and as an increase in $R=\sigma_t/\sigma_{\mu\mu}$ $\left(\sigma_{\mu\mu}=\frac{4\pi\alpha^2}{3s},\ s=\text{square of the c.m. energy}\right)$ due to the production of the $Q\bar{Q}$ continuum. The $Q\bar{Q}$ continuum, which is expected to start some 2 GeV above the first $Q\bar{Q}$ vector state [2], will lead to phase space like events. These events will be distinctly different from the two-jet events that dominate e^+e^- annihilation at high energies. The occurrence of phase space like events is a clear and easily detectable signal for $Q\bar{Q}$ production.

The present paper reports hadron production by e^+e^- annihilation measured at c.m. energies W of 12, 13, 17, 22, 27.4, 27.7, 30, 31.6 GeV and in 20 MeV steps between 29.90 and 31.46 GeV [3]. Measurements of R, sphericity and thrust are presented together with a search for the $t\bar{t}$ continuum. The data are sensitive to a $t\bar{t}$ contribution whose threshold is below 31 GeV.

The experiment was performed at the DESY storage ring PETRA using the TASSO detector. The luminosity provided by PETRA was typically $3\text{–}7\cdot 10^{30}\ \text{cm}^{-2}\,\text{s}^{-1}$ at the beginning of a fill for the high energy running. The detector and the analysis procedure as well as physics results [3–6] have been reported previously. The multihadron events were analyzed in the central detector which measured charged particles over 87% of the full solid angle.

The trigger for $W=12$ GeV required at least 2 charged tracks (3 charged tracks for $W=13\text{–}17$ GeV, and 4 charged tracks for $W\geqq 22$ GeV) with a momentum perpendicular to the beam direction $p_{xy}\gtrsim 0.32$ GeV/c. The offline selection of events, slightly modified from our previous publications [4, 5], was done in three steps. In the first step, at least 3 tracks were required in the x, y plane with at least two of the three fully reconstructed in space. The three tracks should have $d\leqq 2.5$ cm, and the two tracks $|z|<10$ cm, where d is the distance of closest approach to the origin in the (x, y) plane, and z is the coordinate at the point of closest approach to the z axis (=beam direction). In the second step a tight selection of tracks was made. To be considered further a track had to fulfill the following requirements:

1. Reconstruction in space.
2. $d<5$ cm.
3. $p_{xy}>0.1$ GeV/c.
4. $|\cos\theta|<0.87$ where θ is the track angle with respect to the beam axis.
5. $|z-z_V|<20$ cm where z_V is the z coordinate of the event vertex averaged over the tracks.
6. In order to suppress electrons from photon conversion in the material before the drift chamber ($\sim$0.13 radiation lengths) a cut was made for $\gamma\to e^+e^-$ pairs. The corresponding tracks were removed; their momenta were kept in the momentum sum (see below), however. The efficiency of the cut was approximately 55%.

The inefficiency for track reconstruction was found to be 3%. Approximately 0.5% of the reconstructed tracks were spurious. The momentum resolution for charged particles was $\sigma_p/p\approx 2\%\cdot p$ (p in GeV/c) for momenta above 1 GeV/c.

In the third step of the analysis events were selected according to the following criteria:

1. At least 4 (5) accepted tracks for $W=12$–22 GeV ($W\geqq 27.4$ GeV).
2. To remove τ decays, events with one track in one hemisphere and in the other hemisphere 3 ($W\leqq 13$ GeV) or $\geqq 3$ ($W\geqq 17$ GeV) tracks, whose invariant mass (assuming pion masses) was less than 1.78 GeV, were rejected.
3. For the $W=12$ and 13 GeV data, tracks were required in both hemispheres oriented along the beam, and the sum of the charge of the accepted tracks must not exceed 3.
4. The z coordinate of the vertex had to be $|z_V|<6$ cm.

Figure 1a shows the sum of the particle momenta, $\sum|\mathbf{p}_i|$, ~~for~~ the data at $W=29.9$–31.6 GeV after these cuts were made.

A further cut required:

5. $\sum|\mathbf{p}_i|$ to exceed 3 GeV/c at $W\leqq 13$ GeV/c, 4 GeV/c at 17 GeV, 5 GeV/c at 22 GeV and 8 GeV/c at the higher energies.

These events were inspected visually and 1% were discarded as spurious. The final event sample surviving these cuts is essentially free of background from beam gas or beam-pipe interactions, $\gamma\gamma$-interactions, τ pair production, and QED processes.

Table 1 lists the number of accepted events. The detection efficiency was determined by Monte Carlo methods, whereby events were generated via quark antiquark [7] and quark antiquark gluon formation [8] and tracked through the detector. The efficiency was found to be about 80% and to depend little on the specific parameters used to describe the production process. For example at $W=30$ GeV the efficiency computed for $q\bar{q}$ with a transverse momentum parameter $\sigma=450$ MeV/c was $\varepsilon=79\%$ while $q\bar{q}g$ with $\sigma=300$ MeV/c yielded $\varepsilon=82\%$.

The luminosity was determined from small angle Bhabha scattering observed in the forward detector. Radiative corrections to the luminosity measurements were made following [9]. The uncertainty in the luminosity was mainly systematic and was estimated to be $^{+5}_{-8}\%$. Radiative corrections on R were determined by using the published data on R below 10 GeV [10] together with the measurements from this

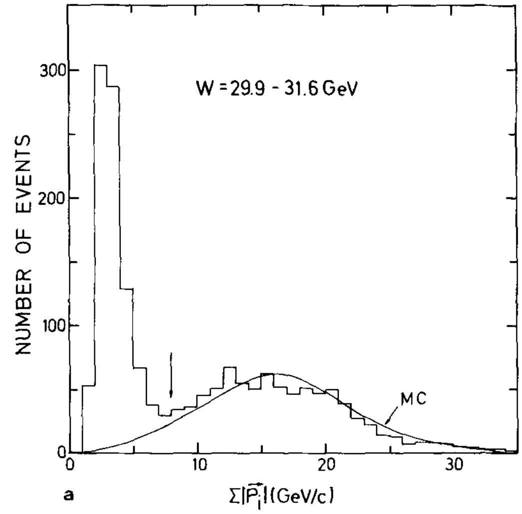

Table 1. Number of accepted multihadron events, integrated luminosity, and measured R values with statistical and systematic errors

W(GeV)	Number of events	Luminosity (nb^{-1})	R
12	194	97	$4.0 \pm 0.4 \pm 0.4$
13	72	30	$5.4 \pm 0.8 \pm 0.6$
17	38	39	$3.1 \pm 0.6 \pm 0.3$
22	25	45	$3.2 \pm 0.8 \pm 0.3$
27.4–27.7	133	330	$3.9 \pm 0.4 \pm 0.4$
29.9–30.9	559	1631	$4.0 \pm 0.2 \pm 0.4$
30.9–31.6	257	807	$3.7 \pm 0.3 \pm 0.4$

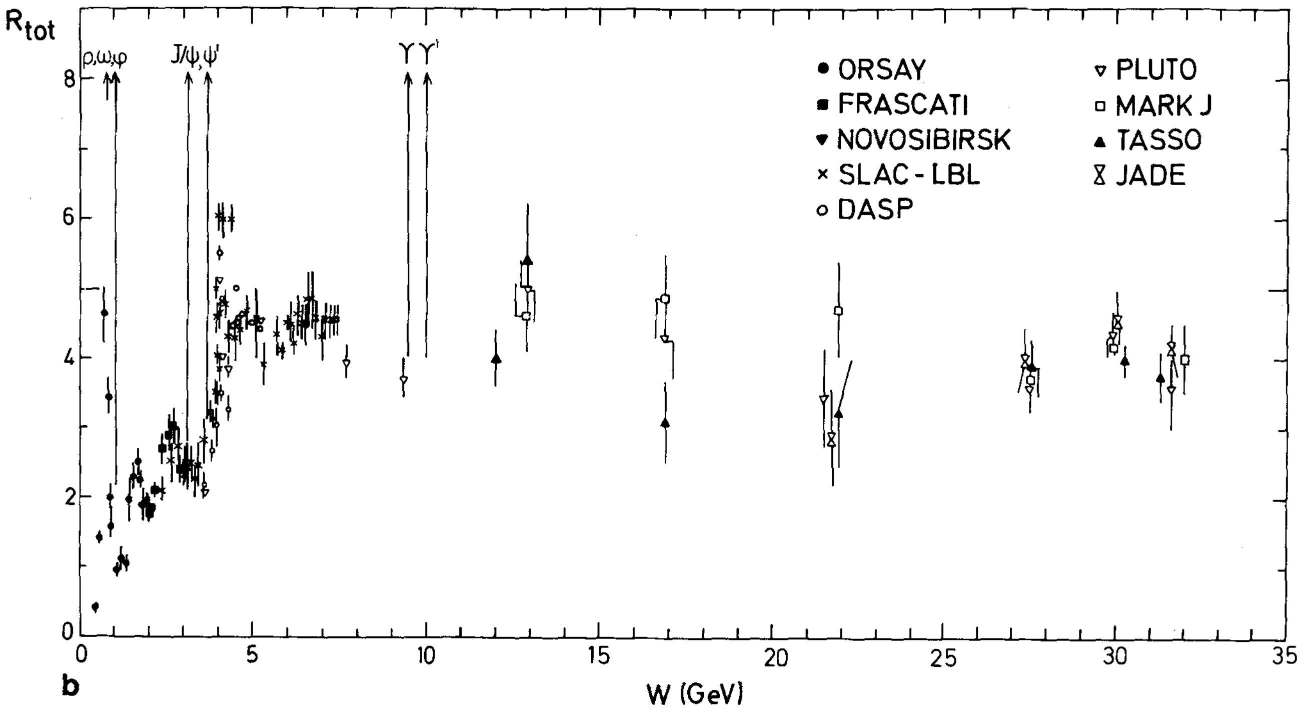

Fig. 1. a Distribution of the sum of charged particle momenta for hadronic candidates at c.m. energies between 29.9 and 31.6 GeV. The solid curve shows the prediction for hadron production through one-photon annihilation in the $q\bar{q}g$ model. The arrow indicates the cut made to select events from annihilation. **b** The ratio R of the total hadronic cross section σ_t to $\sigma_{\mu\mu} = (4\pi\alpha^2)/(3s)$ as a function of the c.m. energy. Data from other experiments are included

experiment. Specifically it was assumed that the R values vary linearly between available data points. In addition, a correction of -6% due to vacuum polarization was made[1]. The radiative corrections reduce the observed cross sections by typically 0.5 units of R. Note that because of the high R value measured at 13 GeV the radiative corrections depress particularly the final values at 17 and 22 GeV.

The resulting R values are listed in Table 1 together with their statistical and systematic ($\pm 10\%$) errors. The R values are shown in Fig. 1b together with the published data [10–13]. Our data agree with those from other PETRA experiments [11–13]. The data at and above 17 GeV are consistent with $R = 3.5$–4. The simple quark model including u, d, s, c, and b predicts $R = 3.7$ and QCD corrections are expected to raise this

1 This correction includes μ pairs, τ pairs, vector meson resonances, and the hadronic continuum. This has not been done previously [4]. The usual correction for e pairs and vertex corrections were done as in our previous papers

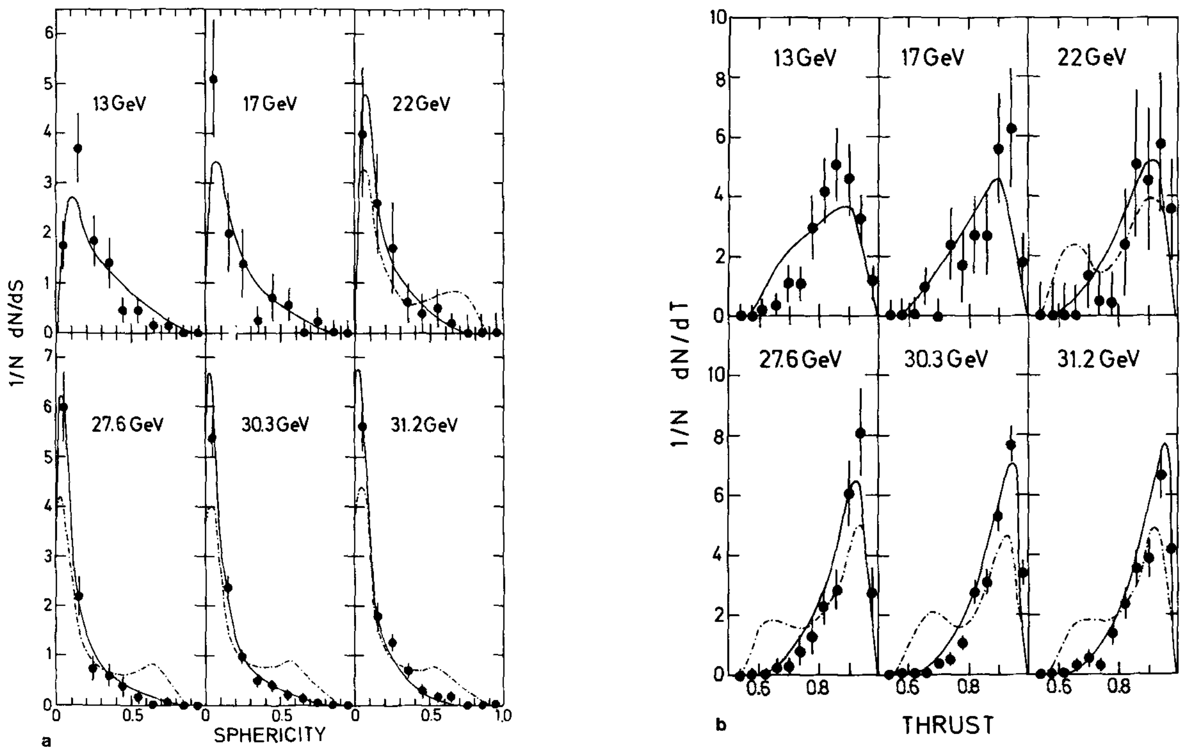

Fig. 2. **a** Sphericity distributions for different c.m. energies. The curves show the predictions of the quark model with u, d, s, c, b quarks plus gluon corrections (solid) plus a t quark contribution (mass = 10 GeV) (dashed-dotted). **b** Thrust distributions for different c.m. energies. The curves have the same meaning as in **a**

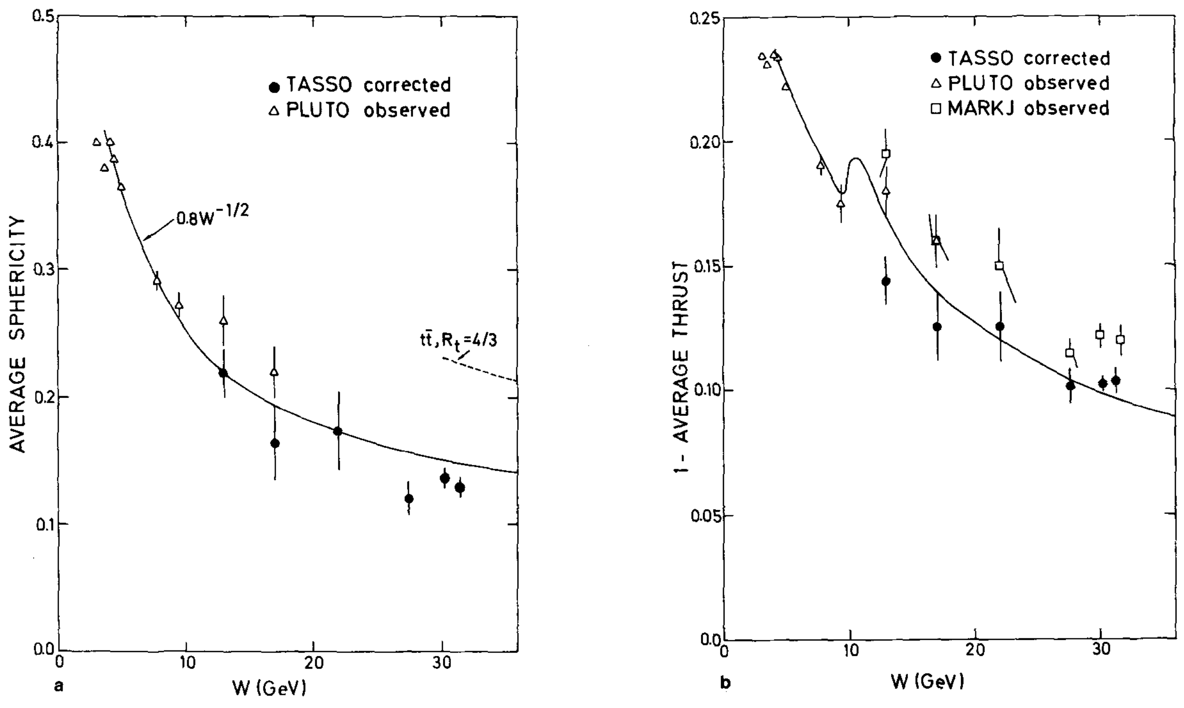

Fig. 3. **a** The average sphericity as a function of the c.m. energy. Data from [11] and [14] are also included. The solid line shows the function $0.8W^{-1/2}$. **b** The average thrust as a function of the c.m. energy. Data from other experiments [11, 12, 14] are included. The solid line represents the QCD prediction [15], smeared for pionization. This smearing had not been done in [15]

by $\approx 10\%$. This agrees with our measurements at and above 17 GeV. The somewhat higher R value at 13 GeV may be due to $b\bar{b}$ production.

The contribution of the hypothetical t quark would increase R by at least $R_t = 4/3$ to $R > 5$ if W is above the threshold for top meson production. Our data show no evidence for such a contribution.

The jet structure of the multihadron events was studied in terms of sphericity, S and thrust T,

$$S = \mathrm{Min}\left(\frac{3}{2}\frac{\sum p_{Ti}^2}{\sum p_i^2}\right), \quad 0 \leqq S \leqq 1;$$

$$T = \mathrm{Max}\left(\frac{\sum |p_{\|i}|}{\sum |p_i|}\right), \quad \tfrac{1}{2} \leqq T \leqq 1.$$

$p_{\|i}$ and p_{Ti} are the longitudinal and transverse momenta of the charged hadron, relative to the jet axis. In order to have a large acceptance for charged particles the distributions of sphericity and thrust were determined for events with $|\cos\theta_{\text{jet}}| < 0.8$, where θ_{jet} is the angle between the jet and the beam axis. The distributions were corrected for acceptance. In Fig. 2a and b the sphericity and thrust distributions for charged particles are displayed for the different energies. Both types of distributions show the trend to ever stronger collimation ($S \to 0$, $T \to 1$) as the energy increases. The curves show the prediction of the quark model with u, d, s, c, and b quarks plus gluon emission (solid lines). They describe the data well.

In Fig. 3 the energy dependences of the acceptance corrected average sphericity $\langle S \rangle$ and thrust $\langle T \rangle$ are shown together with results from other experiments [11, 12, 14]. The increasing collimation with rising energy is clearly borne out by the data. The observed energy dependence of $\langle S \rangle$ can be described approximately by a power law, $\langle S \rangle = 0.8 \cdot W^{-1/2}$. The rate of shrinkage observed is smaller than that expected from the $q\bar{q}$ model [7], $\langle S \rangle \propto W^{-1}$, but in agreement with jet broadening due to gluon bremsstrahlung. The QCD corrected prediction [15] for $\langle T \rangle$ is shown by the solid curve in Fig. 3b.

As mentioned before the event shape is very sensitive to contributions from the continuum production of $t\bar{t}$. The $t\bar{t}$ events are expected to have a high particle multiplicity and a phase space like configuration near threshold. According to the Kobayashi-Maskawa generalized Cabibbo matrix [16] the favoured decay sequence for t quarks is $t \to b \to c \to s$. As a consequence $t\bar{t}$ decays may have 14 or more quarks in the final state, presumably leading to a large hadron multiplicity. At threshold the t, $\bar{t}$ quarks are at rest and will emit hadrons more or less isotropically. As the energy increases the t, $\bar{t}$ quarks receive a boost and the events start to become two-jet like. However, this happens only well above threshold. For example a t quark of 10 GeV mass reaches a velocity of $\beta = 0.7$ only at $W = 28$ GeV, i.e. 8 GeV above threshold. This implies that just above threshold one cannot miss the $t\bar{t}$ continuum contribution [17].

The final state particles from $t\bar{t}$ events near threshold will be distributed phase space like leading to an average sphericity of $\langle S_{PS} \rangle \simeq 0.5$ [17]. The dashed-dotted curves in Fig. 2 indicate the expected S and T distributions in the presence of the $t\bar{t}$ contribution assuming $R_t = 4/3$. The data show no evidence for such a contribution. The $t\bar{t}$ contribution will also lead to an increase in $\langle S \rangle$. The size of this increase can be readily estimated. The average S for the u, d, s, c, b contribution e.g. at 30 GeV is $\langle S_{u,d,s,c,b} \rangle = 0.15$. Averaging over the two components predicts for $\langle S \rangle$ above the $t\bar{t}$ threshold

$$\langle S \rangle = \frac{R_t \langle S_{PS} \rangle + R_{u,\ldots,b} \langle S_{u,\ldots,b} \rangle}{R_t + R_{u,\ldots,b}} \approx 0.23$$

corresponding to an increase of $\simeq 0.08$. If the $t\bar{t}$ contribution rises rapidly at threshold to $R_t = 4/3$ one would expect a step in $\langle S \rangle$. The data do not show such a step (see Fig. 3a).

Sphericity measures the degree of collinearity of the final state particles. Two-jets events tend to be collinear, three-jet events from gluon bremsstrahlung tend to be planar, while phase space like events are noncollinear and nonplanar. For this reason an inspection of the events in terms of sphericity and aplanarity provides an even more stringent test on a $t\bar{t}$ (or other heavy quark) contribution.

In order to study the event shape we use the same method employed to detect 3-jet events [5]. For each event the momentum tensor ellipsoid is constructed from the hadron momenta [18]:

$$M_{\alpha\beta} = \sum_{j=1}^{N} p_{j\alpha} p_{j\beta} \qquad (\alpha, \beta = x, y, z)$$

summing over the N observed charged particles. Let $\hat{n}_1$, $\hat{n}_2$, and $\hat{n}_3$ be the unit eigenvectors of this tensor associated with the normalized eigenvalues Q_i, $Q_i = \sum(\mathbf{p}_j \cdot \hat{n}_i)^2 / \sum p_j^2$, which are ordered such that $Q_1 \leqq Q_2 \leqq Q_3$. Note that $Q_1 + Q_2 + Q_3 = 1$. The principal axis is the $\hat{n}_3$ direction (= sphericity axis), the event plane is given by $\hat{n}_2$, $\hat{n}_3$; $\hat{n}$ defines the direction in which the sum of the square of the momentum components is minimized.

The events can be expressed in terms of two variables, sphericity S and aplanarity A,

$$S = \tfrac{3}{2}(Q_1 + Q_2) = \tfrac{3}{2}(1 - Q_3)$$

$$A = \tfrac{3}{2} Q_1 .$$

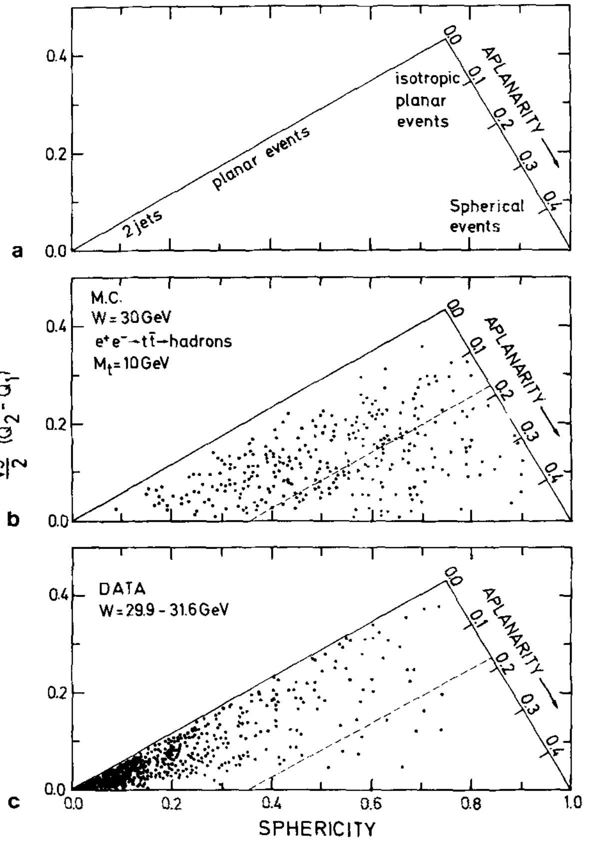

Fig. 4a–c. Distribution of events as a function of aplanarity $A=3/2Q_1$ and sphericity $S=3/2(Q_1+Q_2)$; **a** illustrating the regions for two-jet, planar and spherical events; **b** for Monte Carlo generated events from $t\bar{t}$ production, assuming a t mass of 10 GeV and $W=30$ GeV; **c** for real events at c.m. energies between 29.9 and 31.6 GeV. The dashed lines indicate the aplanarity cut at 0.18

Figure 4 shows the triangle plot distribution in terms of S and A. The sketch given in Fig. 4a indicates the areas for collinear ($S\approx 0$), noncollinear coplanar ($S\neq 0$, $A\approx 0$) and for spherical events (S and A large). Figure 4b shows the event distribution expected from the $t\bar{t}$ contribution. It was computed for $W=30$ GeV under the conservative assumption that the t mass is 10 GeV and propagating the particles from t fragmentation through the detector. The $t\bar{t}$ events populate the triangle plot rather uniformly. Figure 4c shows for comparison the distribution for events observed at $W=29.9$–31.6 GeV. They concentrate in the collinear, planar corner ($S\approx 0$, $A\approx 0$), and only few events are observed at large S and A.

Assuming at $t\bar{t}$ contribution of $R_t=4/3$ one can compare the observed and expected number of events with large S and large A values. As shown in Table 2 we expect from $t\bar{t}$ production 80 events for $A>0.18$ while only 10 are observed. Furthermore, of the 10 events observed, 8 stem from gluon bremsstrahlung according to QCD. A t quark contribution is clearly ruled out by the data. This is also true when the t mass is reduced to 8 GeV. Therefore the data exclude a possible $t\bar{t}$ continuum of strength $R_t=4/3$ between $W=16$ and 31 GeV. A similar conclusion, though with less statistics, was reached in [19]. The data also indicate that the continuum contribution from a heavy quark Q of charge 1/3 ($R_Q=1/3$) appears unlikely: assuming the Q to decay in a manner similar to the t quark 20 events are predicted as compared to the 2 ± 4 events observed after subtracting the $q\bar{q}g$ contribution.

In summary, $R=\sigma_t/\sigma_{\mu\mu}$ is found to be approximately constant for c.m. energies between 17 and 31.6 GeV with a value close to 4. The sphericity and thrust distributions show that the jet cone shrinks with energy. However, the rate of shrinkage as measured e.g. by the average sphericity $\langle S\rangle$ is much slower, $\langle S\rangle\sim W^{-1/2}$, than expected for processes with fixed transverse momentum and logarithmically rising multiplicity ($\langle S\rangle\sim W^{-1}$). From R, from the S and T distributions, and from the analysis of the event shapes a contribution of a possible $t\bar{t}$ continuum with size $R_t=4/3$ can be excluded for c.m. energies between 16 and 31 GeV. Also, the continuum contribution of a charge 1/3 quark appears improbable.

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Table 2. Search for a heavy quark Q contribution, assuming the Q to decay as the hypothetical t quark. Comparison of the number of events observed for aplanarity $A>0.18$ with the prediction of the quark-model for u, d, s, c, b production plus gluon correction and for $Q\bar{Q}$ production alone. The $Q\bar{Q}$ estimate assumed a Q mass of 8 GeV or 10 GeV and a contribution to R of $R_Q=3e_Q^2$ where e_Q is the charge of the quark

W	Number of events					
(GeV)	Observed	Predicted:	$m_Q=10$ GeV		$m_Q=8$ GeV	
		u, d, s, c, b + gluon	$Q\bar{Q}, e_Q=2/3$	$Q\bar{Q}, e_Q=1/3$	$Q\bar{Q}, e_Q=2/3$	$Q\bar{Q}, e_Q=1/3$
29.9–31.6	10	8.2 ± 1.0	80 ± 8	20 ± 2	45 ± 3	11 ± 1
30.9–31.6	2	2.6 ± 0.4	25 ± 2.5	6 ± 0.6	14 ± 1	3.5 ± 0.2

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