# PROPERTIES OF HADRON FINAL STATES IN $e^+e^-$ ANNIHILATION AT 13 GeV AND 17 GeV CENTER OF MASS ENERGIES

TASSO-Collaboration

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We have observed $e^+e^-$ hadrons at C.M. energies of 13 GeV and 17 GeV at PETRA using the TASSO detector. We find $R$(13 GeV) = 5.6 ± 0.7 and $R$(17 GeV) = 4.0 ± 0.7. The additional systematic uncertainty is 20%. Comparing inclusive charged hadron spectra we observe scaling between 5 GeV and 17 GeV for $x = p/p_{\mathrm{beam}} > 0.2$, however the 13 GeV cross section is above the 17 GeV cross section for smaller $x$ This may be due to copious $b\bar{b}$ production. The events become increasingly jet like at high energies as evidenced by a shrinking sphericity distribution with increasing energy.

For footnotes, see next page.

We report results on hadron production in $e^+e^-$ annihilation at C.M. energies of 13 GeV and 17 GeV. The results were obtained at the DESY $e^+e^-$ colliding ring PETRA using the TASSO detector.

Fig. 1 shows a side view of the TASSO detector. It consists of a large magnetic solenoid, 440 cm long and with a radius of 135 cm producing a field of about 0.5 tesla parallel to the beam axis. The field of the solenoid is compensated by two coils placed symmetrically with respect to the central magnet. The solenoid is filled with tracking chambers and will be surrounded by detector elements to measure the energy and position of photons and to identify charged particles. Only the inner part, used in the experiment reported here, will be discussed in more detail. A luminosity monitor, which measures small angle Bhabha scattering, consists of 8 counter telescopes mounted symmetrically with respect to the beam line and interaction point. The mean scattering angle accepted is 45 mrad.

A particle, emerging from the interaction region, traverses the beam pipe and one of four scintillation counters which form a cylinder around the pipe, before entering a low mass cylindrical proportional chamber, a drift chamber, and a set of time of flight counters.

The proportional chamber is 140 cm long with inner and outer radii of 18 and 28.6 cm. It is made of concentric Styrofoam shells each 1.6 cm thick forming 4 active gaps each of 1.4 cm. Each gap has 480 anode wires mounted parallel to the axis with the corresponding wire of each of the 4 gaps positioned at the same azimuthal angle. Each gap has 120 inner and 120 outer cathode strips forming helices having opposite sense of rotation and an average pitch of 36.5°. The strips were made by etching copper coated Kapton film with width and spacing proportional to the radius, the average width is 0.8 cm. The chamber uses "magic" gas, viz. ~75% Argon, 25% Isobutane, 0.25% Freon and a small amount of Methylal (1/4 of the Argon is bubbled through Methylal at 2°C). The efficiency of the anode wires was 97%.

The drift chamber has a sensitive length of 323 cm with inner and outer radii of 36.6 and 122.2 cm respectively. The chamber volume is divided into 6 gaps using

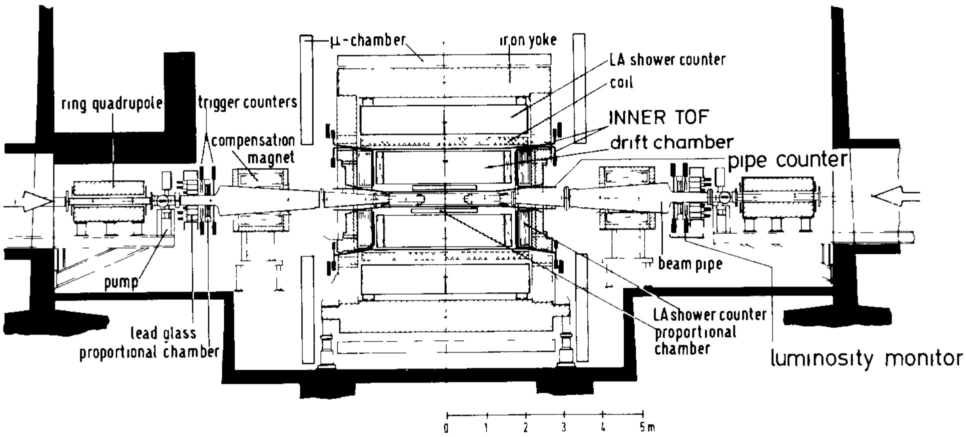


Fig. 1. Side view of the TASSO detector.

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aluminized Rohacell cylinders. The entire chamber has 15 layers, 9 with the sense wires parallel to the axis (zero-degree layers) and 6 with the sense wires oriented at an angle of approximately ±4° to the axis (stereo layers). The layers are spaced 6.1 cm apart. There is a total of 2340 drift cells, each with radial and azimuthal dimensions of 1.2 cm and 3.2 cm, respectively. Argon and Methane mixed in a ratio of 9 : 1 was used. The chamber was found to be 96% efficient per layer including electronic failures; excluding electronic failures the efficiency was 99%.

A set of 48 inner time of flight scintillation counters TOF is mounted in the free space between the drift chamber and the coil at a radius of 132 cm. Each scintillator ($390 \times 17 \times 2$ cm$^3$) is viewed from both ends by RCA 8575 photomultipliers.

During the experiment PETRA operated with two bunches of $e^+$ and two bunches of $e^-$ with about 1 mA (2 mA) in each bunch at 13 GeV (17 GeV) C.M. energy resulting in a typical luminosity of $2 \times 10^{29}$ cm$^{-2}$ s$^{-1}$ ($5 \times 10^{29}$ cm$^{-2}$ s$^{-1}$) at the beginning of a fill.

The data were collected using the following trigger: A coincidence between a beam pick up signal, any beam pipe counter, and any TOF counter gated information from six of the nine zero degree layers of the drift chamber into a hardwired logic unit. The unit searched for tracks and determined their momenta transverse to the beam within 4 $\mu$s. Events with more than a preselected number of tracks having transverse momenta above a chosen value were accepted. The trigger demanded either two tracks coplanar with the beam axis or at least three tracks. The transverse momentum of these tracks with respect to the beam axis was required to exceed 320 MeV/$c$. The resulting trigger rate, after removing the cosmic ray events by an on-line software cut, was roughly 1 Hz.

The luminosity was determined from independent measurements of the Bhabha cross section at small and at large scattering angles. From the luminosity monitor we obtained an integrated luminosity of 31.0 nb$^{-1}$ at 13 GeV and 39.2 nb$^{-1}$ at 17 GeV. Pairs with scattering angles between 36.9° and 143.1° (ee and $\mu\mu$ pairs) were measured using the central detector. The angular distribution agreed with QED. The resulting luminosity was (29.6 ± 3.0) nb$^{-1}$ and (39.2 ± 3.5) nb$^{-1}$ at 13 GeV and 17 GeV respectively (statistical error only). The two measurements are in good agreement and we use the average value of 30.3 nb$^{-1}$ at 13 GeV and 39.2 nb$^{-1}$ at 17 GeV with an estimated systematic uncertainty of no more than 10%.

Roughly 650000 triggers were collected. The multihadron events were selected from these events using the following two step analysis:

At least 3 tracks were required in the projected ($r$, $\phi$)-plane [‡1] with at least two of the three fully reconstructed in 3 dimensions. The three tracks should have $d \leqslant 2.5$ cm and the two tracks $|z| < 10$ cm, where $d$ is the distance of closest approach to the origin in the ($r$, $\phi$) plane, and $z$ is the $z$ coordinate at the point of closest approach to the $z$ axis. A total of 143 events at 13 GeV and 168 events at 17 GeV passed these criteria.

In the second step these events were examined and required to satisfy the following criteria:

(1) The sum of the absolute values of the momenta must be at least 3.0 GeV/$c$ (4.0 GeV/$c$ at 17 GeV). The sum of the absolute values of the momenta transverse to the beam axis must be at least 2.5 GeV/$c$ (3.0 GeV/$c$ at 17 GeV).

(2) At least one charged track must be in each of the 2 hemispheres oriented along the beam direction.

(3) The excess of positively charged particles must be less than three.

To be considered, a charged particle must have had a transverse momentum above 100 MeV/$c$ and reached at least the sixth zero-degree layer in the drift chamber. This imposes an angular cut of $|\cos\theta| \leqslant 0.87$.

A total of 78 events at 13 GeV and 42 events at 17 GeV remained. To estimate the background from beam–gas interactions the whole analysis was repeated with $|z| \leqslant 30$ cm. This analysis resulted in 6 additional events at 13 GeV and in 3 additional events at 17 GeV. After subtraction we are left with 75 events at 13 GeV and 40.5 events at 17 GeV.

These events may arise either from one-photon annihilation or from two-photon processes. The number of events expected both from the hadronlike [1] and the pointlike [2] contribution to the two photon effect have been estimated and found to be less than 1 event together for the cuts used at both energies. In the following discussion we assume that all the events result from the annihilation process.

‡1 We use a right handed coordinate system centered on the interaction point with the $z$-direction along the positron direction and positive $y$ pointing upwards.

To determine the total cross section for hadron production the contribution from $\tau$-pair production was subtracted, and the acceptance for multihadron events was evaluated.

$\tau$-pair production will mainly populate low multiplicities [3], approximately one half of the $\tau$ cross section was removed by demanding a charged multiplicity of 3 or more in the trigger. The bulk of the remaining contribution is rejected by removing 4 prong events with total charge 0 having one track in one hemisphere and the other tracks in the opposite hemisphere. A total of two events at 13 GeV and one event at 17 GeV were rejected, compared to estimates of 3 and 2.5 events respectively. Higher multiplicities ($> 4$) resulting from $\tau$ decay will contribute less than 1 event at each energy and are neglected.

The detection efficiency was determined by a Monte Carlo computation using a jet model [4,5] for the production process and propagating the events through the detector including the trigger and the cuts discussed above. The principal features of the data are consistent with the predictions from the jet model as discussed below. The computation yielded a detection efficiency of $\epsilon = 0.77$ at 13 GeV and 0.78 at 17 GeV. Radiative corrections required reducing the observed cross sections by 8% for both 13 and 17 GeV. The final values for $R$, the total hadronic cross section in units of the point-like muon pair production cross section, are

$$R(13\ \text{GeV}) = 5.6 \pm 0.7 \quad \text{and} \quad R(17\ \text{GeV}) = 4.0 \pm 0.7$$

(statistical errors only). Changing the cuts led to values for $R$ in good agreement with the values listed above and we estimate that our overall systematic uncertainty including the luminosity measurement, the two-photon process, $\tau$-pair production, and detection efficiency is no more than 20%. The relative systematic error for the 2 energies is less than 10%. These values for $R$ are in reasonable agreement with the values reported by the PLUTO [6] and MARK J [7] Collaborations.

The naive quark model predicts $R = 3.7$ for energies well above b threshold. The value for $R$ at 17 GeV is in agreement with this prediction; there is a hint that the $R$ value at 13 GeV is higher.

In the quark model the single particle inclusive cross section $(s/\beta)\, d\sigma/dx_E$ should scale [8] as a function of C.M. energy. Here $\beta$ is the velocity of the particle, $x_E = 2E_h/W$, and $s = W^2$, the C.M. energy

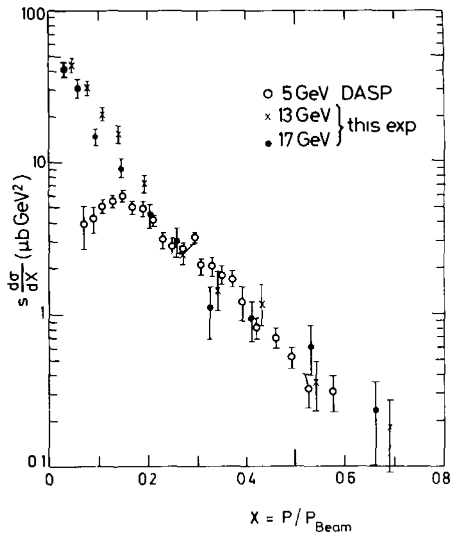


Fig. 2. The cross section $s\, d\sigma/dx$ summed over all charged hadrons versus $x = p/p_{\text{beam}}$ at 13 GeV and 17 GeV. The data are compared with the cross section measured by the DASP Collaboration [9] at 5 GeV.

squared. Since the particle mass is not determined, we used the quantity $s d\sigma/dx$ with $x = p/p_{\text{beam}}$. The inclusive cross sections were determined by using the detection efficiency computed with the jet model [4,5]. The data were corrected for losses due to decay in flight and absorption, assuming the particles to be pions. The decay corrections are less than 9% and the absorption leads to a correction on the average of 4%. A correction was applied for the beam–gas contribution. The radiative corrections led to an overall reduction by 8%. The inclusive cross sections measured at 13 and 17 GeV are plotted in fig. 2. Also shown are the data measured by the DASP collaboration [9] at 5 GeV.

The data are consistent with scaling for $x \gtrsim 0.2$ and C.M. energies between 5.0 GeV and 17 GeV, in agreement with the quark model predictions. The cross section at 13 GeV and 17 GeV are well above the data at 5 GeV for $x < 0.2$. Such a violation of scaling is expected and it gives rise to the increase in multiplicity with $s$. However, at small $x$ ($x \leqslant 0.2$) the cross section at 13 GeV is about 40% above the cross section at 17 GeV, which is 2 standard deviations, including a systematic uncertainty of 10% in the relative normalization. This excess at small $x$ is surprising since from the energy dependence one expects an effect in the opposite direction. This and the large $R$ value observed at 13 GeV is reminiscent of the behaviour seen above charm threshold in the 4 GeV region, and it might indicate copious $b\bar{b}$ production.

It has been conjectured that hadron production in $e^+e^-$ annihilation proceeds by quark pair production with the quarks fragmenting into two roughly collinear jets of hadrons. Data [10] at lower energies from SPEAR and DORIS support this picture. We have compared our data with predictions based on the model, to see if these features persist in the energy range accessible at PETRA.

Several variables, which can be used to characterize the production process have been proposed. Here we evaluate the data using sphericity [11] and thrust [12] defined as follows:

Sphericity

$$S = \frac{3}{2} \min \frac{\Sigma (p_\perp^i)^2}{\Sigma (p^i)^2} .$$

Here $p^i$ is the momentum of a particle and $p_\perp^i$ is its transverse component with respect to a given axis. $S$ approaches 1 for an isotropic event and 0 for a jet like event. Thrust [13]

$$T = \max \frac{\Sigma |p_\parallel^i|}{\Sigma |p^i|} ,$$

where $p_\parallel^i$ is the momentum component along a given axis. Both sums are taken over all observed particles. $T$ is a measure of the maximum directed momentum. It approaches $\frac{1}{2}$ for an isotropic event and 1 for a jet like event.

The normalized sphericity distributions $(1/N)\, dN/dS$ have been plotted in fig. 3 for 13 GeV and 17 GeV separately. The distributions peak at low $S$ and shrink with increasing C.M. energy as expected for jet like events. The difference in shape of the distributions at 13 and 17 GeV may be due to the larger fraction of small $x$ particles observed at 13 GeV in the inclusive distribution.

At 13 GeV the mean value of the sphericity is 0.24 ± 0.02 compared to 0.19 ± 0.03 at 17 GeV. These values are in agreement with the values obtained by PLUTO [6] at the same energies and they are smaller than the value of 0.27 ± 0.01 found [13] at 9.4 GeV. We therefore conclude that the events become more

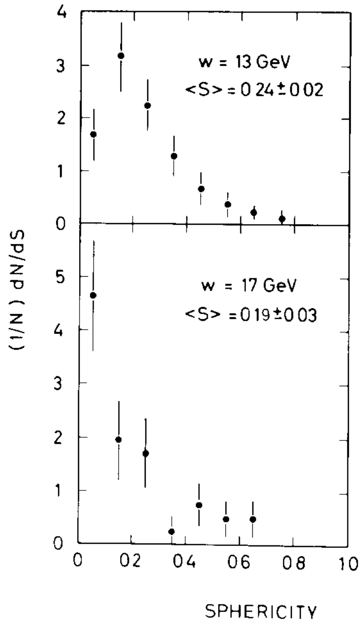


Fig. 3. The sphericity distributions $(1/N)\, dN/dS$ of the data at 13 GeV and 17 GeV The distributions are normalized to the total number of events $N$ observed at each energy

jet-like with increasing energy. The mean thrust values are 0.85 ± 0.01 and 0.87 ± 0.01 at 13 GeV and 17 GeV respectively, compared to 0.824 ± 0.005 at 9.4 GeV [13].

A feature of the jet picture is that the transverse momentum with respect to the jet axis is constant or grows only slowly with energy, whereas the longitudinal momentum will increase more rapidly with energy. We have determined the average values $\langle p_\perp \rangle$ and $\langle p_\parallel \rangle$ defined with respect to the sphericity jet axis. We find $\langle p_\perp \rangle = 0.31 \pm 0.01$ GeV/$c$ at 13 GeV and $0.34 \pm 0.01$ GeV/$c$ at 17 GeV. The average value of the longitudinal momentum with respect to the axis increases from $0.68 \pm 0.05$ GeV/$c$ at 13 GeV to $0.92 \pm 0.05$ GeV/$c$ at 17 GeV.

The simple jet picture with spin 1/2 quarks predicts that the angular distribution of the jet axis should be proportional to $1 + \cos^2\theta$. The angular distribution of the jet axis (defined by sphericity) has been plotted in fig. 4 for the data obtained at 13 GeV and 17 GeV combined. A maximum likelihood fit of the form $1 + a \cos^2\theta$ yielded $a = 1.7 \pm 0.7$, consistent with $1 + \cos^2\theta$.

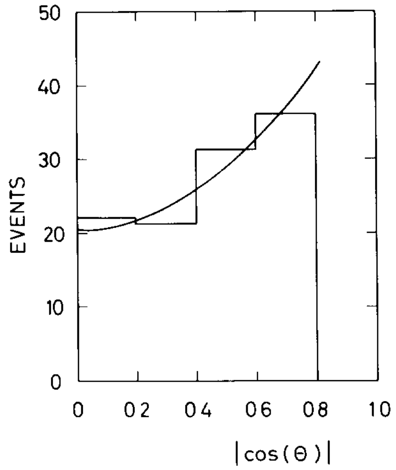


Fig. 4. The angular distribution of the sphericity axis for the 13 GeV and 17 GeV data summed Plotted is the number of events versus cos $\theta$. The solid line is a best fit to the data of the form $1 + a \cos^2\theta$ with $a = 1.7 \pm 0.7$.

We have presented measurements of $R$, the single particle inclusive spectra, sphericity distributions, and the jet axis angular distribution at 13 and 17 GeV C.M. energy. These results are in general agreement with the expectations of a quark–parton jet picture. However, the inclusive spectra show more low-$x$ particles at 13 GeV than at 17 GeV. This plus the difference in $R$ indicate that different physical processes may be involved at the two energies.

We wish to thank the DESY directorate for its strong support of this experiment. The experiment was made possible by the inventiveness and the diligent efforts of the PETRA machine group who succeeded in making PETRA run in a very short time.

The construction of TASSO on this time scale has been a considerable task and would not have been accomplished without the tremendous efforts of the engineers and technicians of the collaborating laboratories. The excellent cooperation with the various technical support groups at DESY and at the Rutherford Laboratory is gratefully acknowledged; in particular we wish to thank Mr. F. Czempik, Mr. B.R. Diplock, Mr. R. Pamperin and Dr. F. Schwickert. We are indebted to Drs. G. Horlitz and G. Sohngen for their assistance. The Wisconsin group would like to thank the Physics Department of the University of Wisconsin for support, especially the High Energy Group and the graduate school research committee.

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