

EVIDENCE FOR PLANAR EVENTS IN e^+e^- ANNIHILATION AT HIGH ENERGIES

TASSO Collaboration

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Hadron jets produced in e^+e^- annihilation between 13 GeV and 31.6 GeV in c.m. at PETRA are analyzed. The transverse momentum of the jets is found to increase strongly with c.m. energy. The broadening of the jets is not uniform in azimuthal angle around the quark direction but tends to yield planar events with large and growing transverse momenta in the plane and smaller transverse momenta normal to the plane. The simple $q\bar{q}$ collinear jet picture is ruled out. The observation of planar events shows that there are three basic particles in the final state. Indeed, several events with three well-separated jets of hadrons are observed at the highest energies. This occurs naturally when the outgoing quark radiates a hard noncollinear gluon, i.e., $e^+e^- \rightarrow q\bar{q}g$ with the quarks and the gluons fragmenting into hadrons with limited transverse momenta.

It has been conjectured that hadron production in e^+e^- annihilation proceeds by quark pair production with the quarks fragmenting into two nearly collinear jets of hadrons [1–4]. The transverse momentum of the hadrons is limited at high energies such that narrow jets are predicted in the PETRA energy range. Data from SPEAR and DORIS support this picture [5,6]. In this paper we examine our data on e^+e^- annihilation at high energies for deviations from the simple quark parton picture⁺¹. Such deviations have been observed [8] in deep inelastic lepton scattering experiments and are expected [9] to occur in any field theory of strong interactions. Furthermore, final states observed [10] in the hadronic decay of the $\Upsilon(9.46)$ disagree with a naive $q\bar{q}$ picture.

This analysis is based on data collected at the DESY e^+e^- storage ring PETRA using the TASSO detector. A description of the experimental setup and of the data analysis has already been published [11]. We list here only the main points. The detector, which measures charged secondaries over approximately 87% of 4π , was triggered by demanding at least three tracks with a transverse momentum of more than 0.32 GeV/c with respect to the beam axis, at total energies $W = 2E_{\text{beam}} = 13$ and 17 GeV. At least four tracks were required at $W = 27.4, 27.7, 30,$ and 31.6 GeV. The hadronic events were separated from the beam gas background by demanding that the event vertex was in the interaction volume, and that the sum of the detected momenta were above 3 GeV/c at 13 GeV energy, above 4 GeV/c at 17 GeV energy, and above 9 GeV/c at the higher energies. Further cuts on the event topology essentially eliminated $\gamma\gamma$ and $\tau^+\tau^-$ events. The resulting detection efficiency varied with energy between 75% and 78%. The final data sample

consists of 75 events at 13 GeV, 40 events at 17 GeV, 118 events at 27.4 and 27.7 GeV, 135 events at 30 GeV, and 40 events at 31.6 GeV. For the following analysis only tracks that reached at least the sixth zero degree layer in the drift chamber ($|\cos\theta| < 0.87$) and had transverse momentum relative to the beam axis of at least 0.10 GeV/c, are used. Hadrons resulting from kaon decays were not removed while electrons from pair conversion or Dalitz decays were removed.

The effects of the selection criteria described above, as well as the effects of measuring errors and the efficiencies of the pattern recognition programs and the whole analysis chain, were checked by propagating Monte Carlo events through the simulated detector and the analysis programs. It was thus ascertained that the results presented in this paper are not subject to any significant bias due to these sources.

The quark parton picture of the process $e^+e^- \rightarrow q\bar{q}$ is depicted in fig. 1a. It will produce back-to-back jets of hadrons with typical transverse momenta of 0.30 GeV/c. In field theories of the strong interactions this picture will be modified [9,12] to include other processes including the lowest-order diagrams shown in fig. 1b. The radiated field quanta (gluons) are also expected to evolve into jets of hadrons. This has clear experimental implications [12–16]: The p_T distribution of the final hadrons will broaden with increasing energy. If the coupling constant is less than one there will be a tendency for only one of the jets to be broadened. The $q\bar{q}g$ state is necessarily planar; this should be reflected in the final hadron configuration which should retain the planarity with small transverse momenta with respect to the plane and large transverse momentum in the plane. If the gluon is radiated with a transverse momentum that is large compared to the typical transverse momentum of 0.30 GeV/c, then the event will have a three-jet topology [12].

Since in e^+e^- interactions the direction of the jet axis is not known from the initial state, it has to be

⁺¹ Evidence for planar events in e^+e^- annihilation has been reported earlier, see ref. [7]. The present results are based on a five-fold increase of statistics.

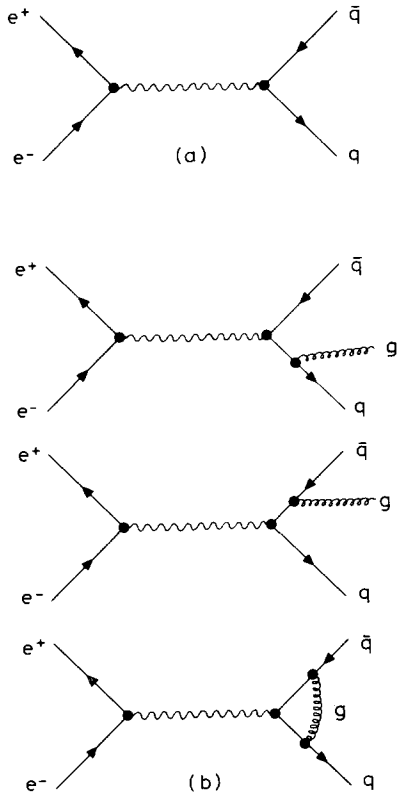


Fig. 1. Quark pair production and gluon bremsstrahlung to lowest order.

determined event by event from the final state hadrons. We have done this in two ways: Minimizing Σp_{\perp}^2 (which gives the sphericity axis) [3,5] or maximizing $\Sigma |p_{\parallel}|$ (which gives the thrust axis) [13,17]. The summations are over all observed hadrons. The results presented in this paper were generally found not to depend to any significant degree on the choice between these two possibilities^{‡2}. Studies with Monte Carlo $q\bar{q}$ jets [18]^{‡3} further showed that the jet axes so determined deviate by an average of less than 5° from the true jet axis at our higher energies.

The normalized transverse momentum distribution $\sigma^{-1} d\sigma/dp_{\perp}^2$ evaluated with respect to the sphericity

^{‡2} An exception is the “seagull effect” shown in fig. 3. Here only the thrust axis is useful since the sphericity weights fast particles too heavily and thus biases the particles of high $z = p_{\parallel}/p_{\text{beam}}$ towards small values of p_{\perp} .

^{‡3} For comparison with the data we used the version given by Field and Feynman [18].

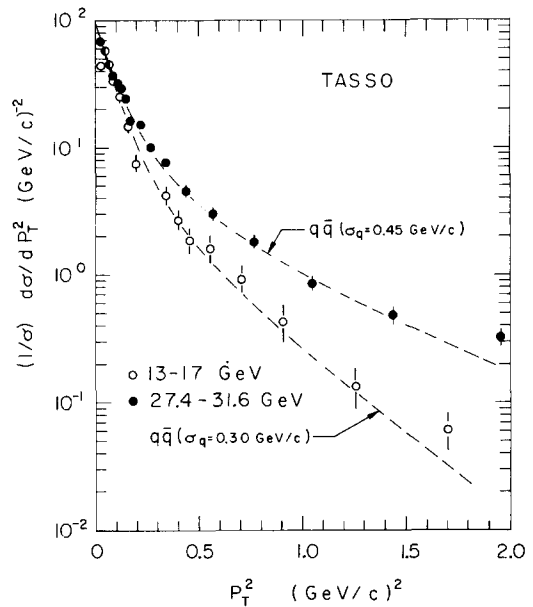


Fig. 2. $\sigma^{-1} d\sigma/dp_{\perp}^2$ at 13 and 17 GeV combined (\circ) and for 27.4 GeV, 27.7 GeV, 30.0 GeV and 31.6 GeV combined (\bullet) as a function of p_{\perp}^2 . The curves are fits to the data for $p_{\perp}^2 < 1.0$ GeV/c using the Field–Feynman quark–parton model including u, d, s, c and b quarks with σ_q as a free parameter.

axis is plotted in fig. 2 versus p_{\perp}^2 . The data at 13 GeV and 17 GeV are identical within statistics and are averaged; similarly the higher energy data between 27.4 GeV and 31.6 GeV are combined. The data at both energies are in reasonable agreement for $p_{\perp}^2 < 0.2$ (GeV/c)² but the high-energy data are well above the low-energy data for larger values of p_{\perp}^2 . The average value of p_{\perp}^2 increases from 0.15 ± 0.02 (GeV/c)² at 13 and 17 GeV, to 0.27 ± 0.02 (GeV/c)² for the combined high-energy data. The low-energy data have been fitted for $p_{\perp}^2 < 1.0$ (GeV/c)² with the jet model [18]^{‡3} of Field and Feynman, extended to include c and b quarks^{‡4}. In this model, the parameter σ_q determining the width of the p_{\perp} distribution was varied from the original value $\sigma_q = 0.25$ GeV/c to $\sigma_q = 0.30$ GeV/c to obtain a fit to our data. This is shown by the curve in fig. 2. To fit the higher-energy data with the Field–Feynman model, σ_q must be increased to 0.45 GeV/c. This is in contradiction to the naive quark parton model which assumes the quark to frag-

^{‡4} The branching ratios for B meson decay were taken from ref. [19].

ment into hadrons with an energy-independent transverse momentum distribution. On the other hand, field theories of the strong interactions naturally predict the transverse momentum to increase with energy due to gluon bremsstrahlung by one of the outgoing quarks. The production of a new quark flavour will also lead to an increase in the average value of p_T . We do not find any evidence for the production of a new flavour in agreement [20] with other groups at PETRA.

If hard noncollinear gluon emission is a rare process, then there should usually be only one such gluon in these events. Dividing each event into two halves by a plane perpendicular to the jet axis and determining $\langle p_T^2 \rangle$ separately for the two sides, the "narrow" side should rarely have a noncollinear hard gluon. Thus $\langle p_T^2 \rangle_{\text{narrow}}$ will increase with energy less rapidly than $\langle p_T^2 \rangle_{\text{wide}}$. This is observed as shown in fig. 3 where $\langle p_T^2 \rangle$ is plotted as a function of $z = p/p_{\text{beam}}$ for the wide and the narrow jet separately. The $q\bar{q}$ model with $\sigma_q = 0.30 \text{ GeV}/c$ is also plotted in fig. 3a. It fits the data rather well at low energy; the narrow-wide asymmetry is due to statistical fluctuations. The model fails to de-

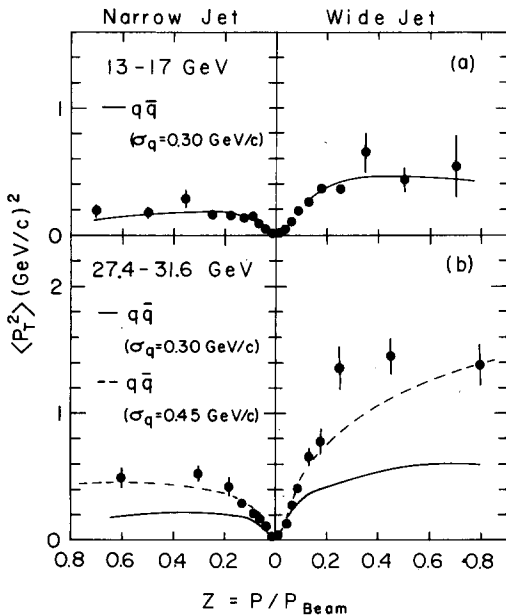


Fig. 3. $\langle p_T^2 \rangle$ as a function of $z = p/p_{\text{beam}}$ for the wide and narrow jet separately, for the low-energy (a) and the high-energy (b) data. The curves show the prediction from the $q\bar{q}$ model [18] ± 3 with $\sigma_q = 0.30 \text{ GeV}/c$ (solid curve) and $\sigma_q = 0.45 \text{ GeV}/c$ (dotted curve). The model includes u, d, s, c and b quarks.

scribe the data at high energies (fig. 3b); however, increasing σ_q to $0.45 \text{ GeV}/c$, obtained from the fit to the p_T^2 distribution, approximately reproduces the observed z distribution. Therefore we can fit, within the statistical uncertainties, both the p_T^2 distributions and the seagull plot at both energies by increasing the value of σ_q with energy.

Regardless of the value of $\langle p_T \rangle$ in the naive quark jet picture hadrons resulting from the fragmentation of the quark must be on the average uniformly distributed in azimuthal angle around the quark axis. Therefore, apart from statistical fluctuations, the two-jet process $e^+e^- \rightarrow q\bar{q}$ will not lead to planar events where as the radiation of a hard gluon, $e^+e^- \rightarrow q\bar{q}g$, will result in an approximately planar configuration of hadrons with large transverse momenta in the plane and small transverse momenta with respect to the plane. Thus the observation of such planar events at a rate significantly above the rate expected from statistical fluctuations of the $q\bar{q}$ jets shows in a model-independent way that there must be a third particle in the final state, which might be identified with a gluon.

The shape of the events is evaluated using the following method. For each event we construct the second-rank tensor [3,5] from the hadron momenta

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

summing over all 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 smallest, intermediate, and largest eigenvalues Λ_1, Λ_2 and Λ_3 , respectively. The principal jet axis is then the \hat{n}_3 direction, the event plane is the \hat{n}_2 - \hat{n}_3 plane, and \hat{n}_1 defines the direction in which the sum of the squared hadron momenta components is minimized [21]. We compare in fig. 4 the distribution of

$$\langle p_T^2 \rangle_{\text{out}} = \frac{1}{N} \sum_{j=1}^N (\mathbf{p}_j \cdot \hat{n}_1)^2$$

(the momentum component normal to the event plane squared) with that of

$$\langle p_T^2 \rangle_{\text{in}} = \frac{1}{N} \sum_{j=1}^N (\mathbf{p}_j \cdot \hat{n}_2)^2$$

(the momentum component in the event plane per-

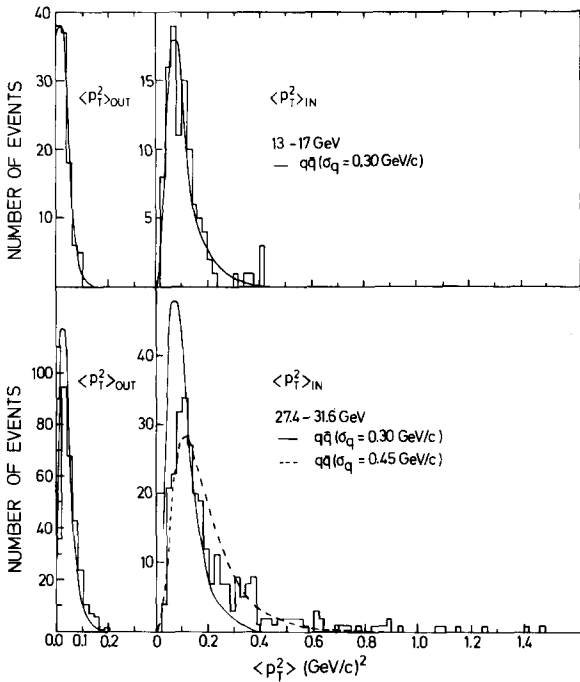


Fig. 4. The mean transverse momentum squared normal to the event plane $\langle p_T^2 \rangle_{out}$ and in the event plane $\langle p_T^2 \rangle_{in}$ per event for the low-energy and the high-energy data. The predictions from the quark model [18] ^{#3} are shown assuming $\sigma_q = 0.30$ GeV/c (solid curves) and $\sigma_q = 0.45$ GeV/c (dotted curve). The model includes u, d, s, c and b quarks.

pendicular to the jet axis). The data show only little increase in $\langle p_T^2 \rangle_{out}$ between the low-energy and the high-energy point. The distribution of $\langle p_T^2 \rangle_{in}$, however, becomes much wider at high energies, and in particular there is a long tail of events with a large value of $\langle p_T^2 \rangle_{in}$ not observed at lower energies. The curves show the expectations from the Monte Carlo $q\bar{q}$ jets. Hadrons resulting from pure $q\bar{q}$ events will on the average be distributed uniformly around the jet axis, however, some asymmetry between $\langle p_T^2 \rangle_{in}$ and $\langle p_T^2 \rangle_{out}$ is caused by statistical fluctuations. Fair agreement with the $q\bar{q}$ model is found both for $\langle p_T^2 \rangle_{in}$ and $\langle p_T^2 \rangle_{out}$ at the low-energy point. Thus the asymmetry observed at this energy can be explained by statistical fluctuations only.

At the high energy, we find fair agreement between $\langle p_T^2 \rangle_{out}$ and the $q\bar{q}$ model with $\sigma_q = 0.30$ GeV/c, however, the observed long tail of the $\langle p_T^2 \rangle_{in}$ distribution is not reproduced by the model. This discrepancy can-

not be removed by increasing the mean transverse momentum of the $q\bar{q}$ jets. The result from the model with $\sigma_q = 0.45$ GeV/c is also plotted in fig. 4. The agreement is poor. We therefore conclude that the data include a number of planar events not reproduced by the $q\bar{q}$ model, independent of the assumption on the average p_T in that model.

The normalized eigenvalues,

$$Q_k = \Lambda_k / \sum_{j=1}^N p_j^2,$$

may be used for a more detailed study of the shape of the events. These normalized eigenvalues Q_k satisfy $Q_1 + Q_2 + Q_3 = 1$ and are arranged such that $0 \leq Q_1 \leq Q_2 \leq Q_3$. We express our data in terms of two variables, aplanarity A and sphericity S :

$$A = \frac{3}{2} Q_1 = \frac{3}{2} \langle p_T^2 \rangle_{out} / \langle p^2 \rangle,$$

$$S = \frac{3}{2} (Q_1 + Q_2) = \frac{3}{2} \langle p_T^2 \rangle / \langle p^2 \rangle.$$

All the events are then inside a triangle shown in fig. 5, where S is the hypotenuse of the triangle. The event distribution in A and S is shown in fig. 5, for the low-energy and high-energy data separately.

Collinear two-jet events lie in the left-hand corner

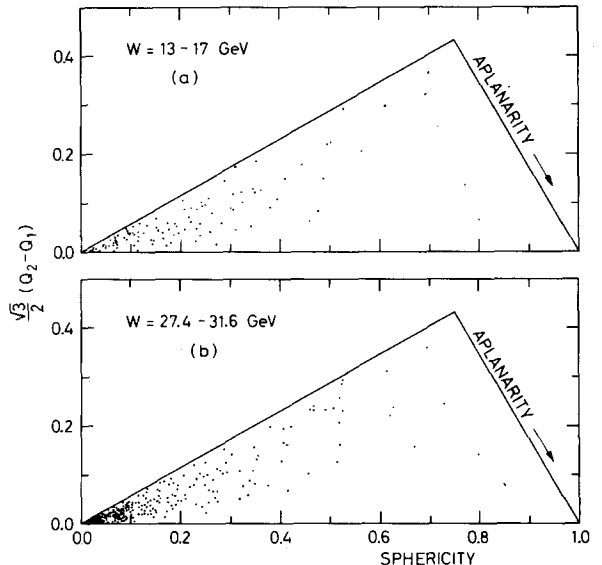


Fig. 5. Distribution of the events as a function of aplanarity $A = \frac{3}{2} Q_1 = \frac{3}{2} \langle p_T^2 \rangle_{out} / \langle p^2 \rangle$ and sphericity $S = \frac{3}{2} (Q_1 + Q_2) = \frac{3}{2} \langle p_T^2 \rangle / \langle p^2 \rangle$ for the low (a) and high (b) energy data.

(A, S small), uniform disk shaped events in the upper corner (A small, S large), and spherical events in the lower right-hand corner (A, S large), while coplanar events will occupy a band along the larger of the two small sides of the triangle in fig. 5.

Collinear two-jet events are seen to dominate at all energies, the collinearity being most pronounced at the highest energy. We exclude these events and select the candidates for planar events by requiring that $A < 0.04$ and $S > 0.25$. At 13 and 17 GeV we observe six events in this region compared to 3.5 events predicted by the $q\bar{q}$ model with $\sigma_q = 0.30$ GeV/c. At the higher energies we find 18 events compared to 4.5 events predicted by the $q\bar{q}$ model, independent of σ_q between 0.30 and 0.45 GeV/c. As an independent test of the planar structure, a randomization procedure^{‡5} was applied to the data to destroy any natural correlations. This estimate of accidentally planar events yields six events in the 13–17 GeV data and four events in the higher-energy data. Thus at the higher energies there is an excess of planar events well above the level predicted from statistical fluctuations of the $q\bar{q}$ jets. This shows that $e^+e^- \rightarrow$ hadrons proceeds via the creation and decay of at least three primary particles that subsequently fragment into hadrons. Field theories of the strong interactions predict such a topology resulting from the radiation of a field quantum (gluon) by one of the quarks, i.e., $e^+e^- \rightarrow q\bar{q}g$.

If this is the correct explanation and the gluon materializes as a jet of hadrons with limited transverse momentum then a small fraction of the events should display a three-jet structure. The events were analyzed for a three-jet structure as described in ref. [21]. All the coplanar events gave a good fit to the three-jet hypothesis. We further determined the transverse momenta of the hadrons with respect to the axis to which they were assigned. For the 18 events defined above we find an average transverse momentum of about 0.30 GeV/c, close to the mean p_T observed in two-jet events at lower energies.

To compare this new class of three-jet events with the predominant class of two-jet events, fig. 6 shows a characteristic event of each type in momentum

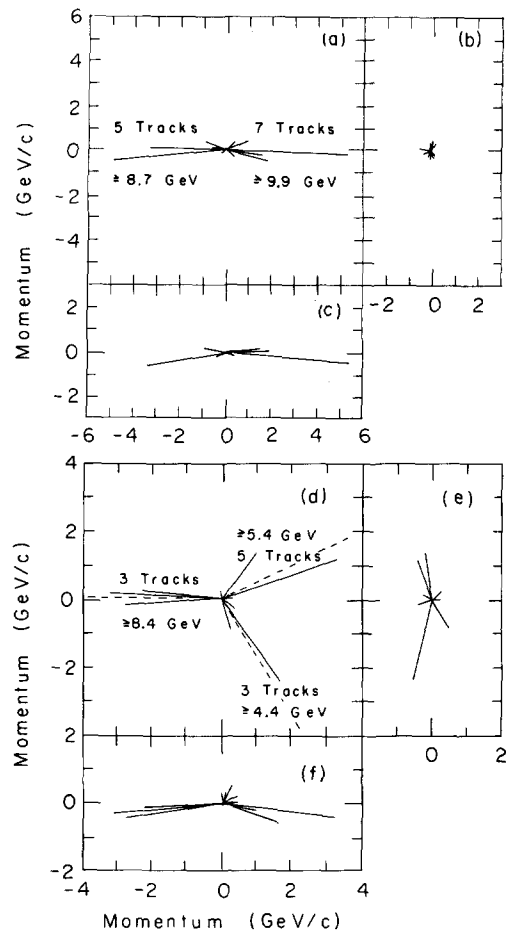


Fig. 6. Momentum space representation of a two-jet event (a)–(c) and a three-jet event (d)–(f) in each of three projections. (a), (d) \hat{n}_2 – \hat{n}_3 plane; (b), (e) \hat{n}_1 – \hat{n}_2 plane; (c), (f) \hat{n}_1 – \hat{n}_3 plane.

space in all three projections. Figs. 6a and 6d show a two-jet and a three-jet event, respectively, in the \hat{n}_2 – \hat{n}_3 plane; this is the plane containing the largest components of momenta. The first event shows two clearly delineated jets. The three-jet event, on the other hand, shows a much broader distribution of momenta transverse to the \hat{n}_3 axis. Figs. 6b and 6e show the projection on the plane perpendicular to the jet direction (\hat{n}_3). Here one clearly sees the small transverse momenta for the two-jet event and the tendency of the large transverse momentum to lie along the \hat{n}_2 direction for the three-jet event. Finally figs. 6c and 6f show the remaining projection on the \hat{n}_1 – \hat{n}_3 plane.

^{‡5} The sphericity axis was chosen as a reference, and all tracks were rotated by a random azimuthal angle around the jet direction; this preserves both p_T and $p_{||}$. Then at random the sign of $p_{||}$ was changed.

In summary, we have studied $e^+e^- \rightarrow$ hadrons for values of Q^2 between $170 (\text{GeV}/c)^2$ and $1000 (\text{GeV}/c)^2$. We observe a change in the p_T^2 distribution and a strong increase of $\langle p_T^2 \rangle$ with increasing energy. This increase occurs predominantly in only one of the two jets. The distribution of the transverse momentum perpendicular to the "event plane" does not show a pronounced energy dependence while a strong broadening takes place in the event plane at the highest values of Q^2 . We observe planar events at a rate which is well above the rate computed for statistical fluctuations of the $q\bar{q}$ jets. The planar events exhibit three axes, the average transverse momentum of the hadrons with respect to these axes being $0.30 \text{ GeV}/c$. This establishes in a model-independent way that a small fraction of the e^+e^- annihilation events proceeds via materialization of three primary particles, each of which materializes as a jet of hadrons in the final state. The data are most naturally explained by hard noncollinear bremsstrahlung $e^+e^- \rightarrow q\bar{q}g$. Indeed, the data are in agreement with predictions based on first-order perturbative QCD as will be discussed in a forthcoming paper.

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