A STUDY OF JETS IN ELECTRON POSITRON ANNIHILATION INTO HADRONS IN THE ENERGY RANGE 3.1 TO 9.5 GeV

PLUTO Collaboration

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From an analysis of data taken with the detector PLUTO at the DORIS storage rings we have obtained evidence for jet structure in e^+e^- annihilation with hadrons. Results for mean sphericity, mean thrust, the angular dependence of the jet axis and for $\langle p_t \rangle$ and $\langle p_{\parallel} \rangle$ with respect to the jet axis are presented. At 9.4 GeV we also discuss the angular dependence of the charged and neutral deposited energy with respect to the jet axis.

One of the most interesting developments in high energy physics in recent years has been the observation of jet structure in multi-hadron final states. Evidence for jets has been seen in electron positron annihilation [1] and in reactions induced by lepton, photon and hadron beams [2]. That jets should exist in deep inelastic processes was a clear prediction of the quark-parton model [3] and more recently of quantum chromodynamic (QCD) theories [4,5]. Originally it had been hoped that by studying jets the quantum numbers of the underlying quarks could be measured by the average quantum numbers of the hadrons in the jet [3]. Later work showed that this connection would probably be very difficult to establish [6]. To date the best evidence for associating jets with a quark origin comes from electron positron annihilation where the angular distribution of the jet axis relative

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to the beam axis has been measured to be that expected for a pair of spin-1/2 particles [1,7].

In this letter we present evidence for jet structure using both sphericity and thrust as jet measures for charged particles. We show that the events become more jet like as the energy increases. By using shower counter information at 9.4 GeV we are able to demonstrate that the inclusion of neutral particles will not change substantially the present picture of jet behaviour.

Data were taken during two periods using the magnetic detector PLUTO at the electron positron storage ring DORIS. The centre of mass energy range 3.1 to 5 GeV, including the J/ψ and ψ' resonances, was covered during 1976 using the original form of the detector as described in ref. [8a]. The energy range 7.7 to 9.5 GeV, including the upsilon resonance, was covered during the first half of 1978 using the detector modified by the addition of shower counters as described in ref. [8b].

Events for the jet analysis were selected by applying the following cuts to the data sample used for the total cross section analysis [8].

(1) At least four fully reconstructed charged tracks coming from the interaction vertex.

(2) To reduce the level of beam–gas background events with 4 or 5 prongs and an excess of positive charge were rejected. We compensate for this cut by doubling the 4 and 5 prong events with an excess of negative charge.

(3) Because the beam–gas background at 9.4 GeV and above was much more severe than that at lower energies a cut on the total observed energy (charged + neutral) of at least 1/2 of the centre of mass energy was applied.

After applying the above cuts any remaining beam–gas background was subtracted by using the distribution of the reconstructed event vertices along the beam direction (at most 7%). With these cuts we see about 40% of the total cross section at low energies and about 60% at the highest energy.

Three sources of background from processes other than one-photon annihilation into hadrons must be considered. They are

(1) multiprong events from τ decays,

(2) multiprong events from the two photon process, and

(3) Bhabha scattering events where at least one particle radiates or develops such a complicated shower that the event is classified as multiprong.

Events from source (1) are difficult to eliminate completely, but since we are using events with 4 or more prongs we estimate that τ decays contribute of the order 10% [9]. The two-photon process (2) could be a problem at the highest energy but is largely removed by the use of the energy cut, we estimate that the residual contamination is less than 5% [10] [‡1]. Bhabha events (3) are potentially the most serious background because they will be very jet-like. To remove them we first construct a measure of the mean angular deviation (σ_Q) of the tracks in an event from collinearity. Events originating from Bhabha scattering congregate at small values of σ_Q allowing a clean separation from hadronic events. At 9.4 GeV we have also checked that the method is efficient on a sample of Bhabha events identified using shower counter information. We find that at most 2% of the final event sample could be classified as of Bhabha origin. Monte Carlo studies indicate a loss of at most 1% of hadronic events due to the σ_Q cut.

We have considered two different methods of measuring the "jetness" of an event and at the same time finding the most likely jet axis. The first, sphericity, is well known. It is defined by

$$S = 3/2 \min \left(\sum_i p_t^{i2} \right) \Big/ \sum_i p_i^2 , \qquad (1)$$

where p_t is the transverse momentum relative to an axis through the event interaction vertex and the sum runs over all observed particles. Sphericity was first proposed by Bjorken and Brodsky [11] and used by the SLAC/LBL collaboration at SPEAR to establish the existence of jets in electron positron annihilation [1]. For an ideal detector and large multiplicity one expects $S \to 1$ for perfectly isotropic events and $S \to 0$ for jet like events.

Because sphericity involves the sums of squares of momenta it has proved difficult to calculate in the QCD framework. This had led to alternative measures of "jetness" being proposed that are linear in momentum. We have used the maximum directed momentum

‡1 At 9.4 GeV we have also checked that we do not see any excess of events with a total visible energy substantially less than the centre of mass energy.

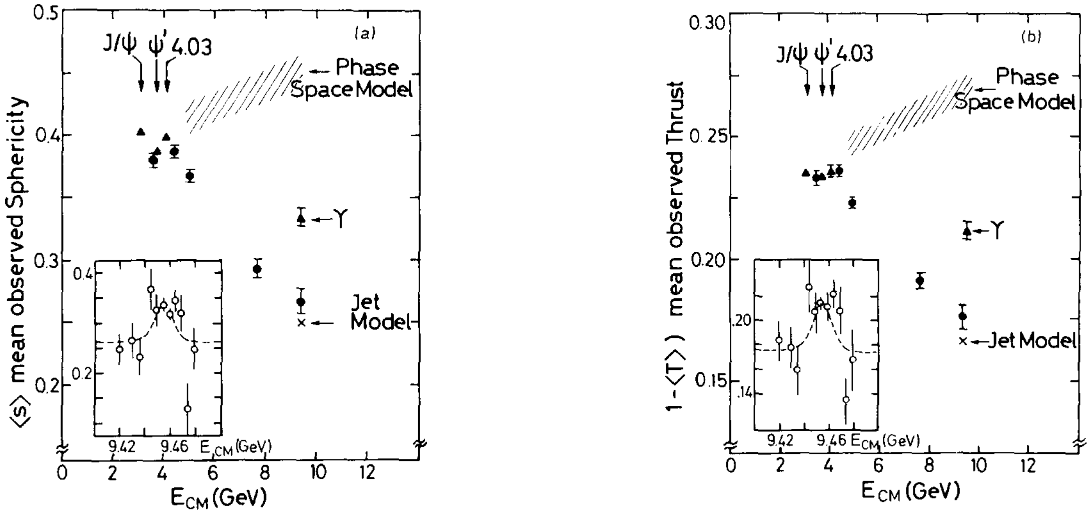

Fig. 1. (a) Mean observed sphericity ⟨S⟩ for events with at least four charged tracks as a function of the centre of mass energy. The triangles are data taken on the resonances indicated, the full points are off resonance data. (b) As for fig. 1a but showing $1 - \langle T \rangle$, where ⟨T⟩ is the mean observed thrust. In each figure the hatched area indicates the expectation from the isotropic Monte Carlo and the cross shows the result of the jet Monte Carlo based on ref. [6]. Note that the data point at the ψ' resonance includes events from the cascade decays, and that no continuum subtraction has been performed on the data at the upsilon resonance. The inset shows the data in the upsilon region together with a gaussian curve with the mass and width from our fit to the total cross section [8b] but normalised to the data shown here.

[12] or "thrust" [5] defined by ‡2,

$$T = 2\max\left(\tilde{\sum_i} p_i^{\parallel}\right) \Big/ \sum_i |\boldsymbol{p}_i| , \qquad (2)$$

where the sum $\tilde{\Sigma}$ runs over one hemisphere only. $p_i^{\parallel}$ is the component of $\boldsymbol{p}_i$ parallel to an axis through the common event vertex and the event is divided into hemispheres by the plane normal to this axis through the vertex. For an ideal detector and large multiplicity $T \to 1/2$ for isotropic events and $T \to 1$ for jet-like events [5].

We have found the above definition of thrust to be somewhat impractical. In an event in which there is missing momentum the visible thrust can be greater than 1. To overcome this problem we have replaced the above definition by

$$T = \max\left(\sum |p_i^{\parallel}|\right) \Big/ \sum_i |\boldsymbol{p}_i| , \qquad (3)$$

where the sum in both numerator and denominator now runs over all observed particles. For an event with no missing momentum the two definitions are identical. An elegant way of finding the direction which maximizes T (the "thrust axis") is given in ref. [13].

At the energies we are considering, the average multiplicity is far from large and the values for sphericity and thrust for phase space events will deviate considerably from the limiting values of 1 and 1/2 respectively. To account for this effect and to allow for the detector acceptance and analysis cuts, we have used an isotropic phase space Monte Carlo to provide the expected values for isotropic events.

The other study that we have done to understand our measurements is to use the quark fragmentation model of Field and Feynman [6] as the basis for a jet Monte Carlo ‡3. To the extent that this model has been designed to fit jet data from lepton and hadron induced processes we can see how well our measurements agree with the jet properties seen in these reactions.

Before discussing our results we emphasize that

‡2 The name "thrust" was coined by the authors of ref. [5] who reviewed QCD calculations for electron positron annihilation, but it is in fact identical to the "principal axis" method proposed by Brandt et al. in 1964 [13].

‡3 We thank H.G. Sander for providing us with an event generator based on ref. [6].

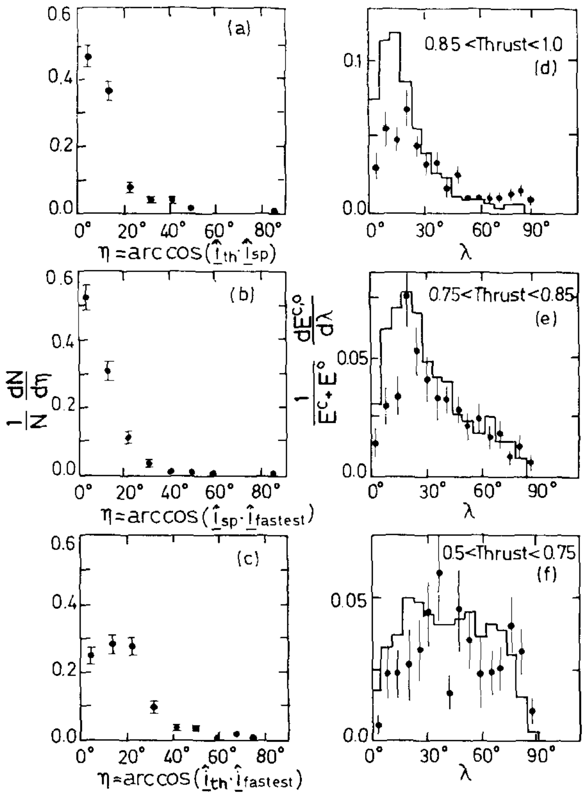

Fig. 2. (a) The distribution of the angle between the sphericity and thrust axes at 9.4 GeV. The symbol $\hat{1}$ denotes a unit vector along the jet axis. (b), (c) The distributions of the angle between the charged particle with largest momentum and the sphericity and thrust axes respectively at 9.4 GeV. (d)–(f) The angular distributions $(1/E)(dE^c/d\lambda)$ of charged energy (histograms) and $(1/E)(dE^0/d\lambda)$ neutral energy (data points) with respect to the thrust axis at 9.4 GeV for thrust bins 0.85–1.0, 0.75–0.85 and 0.5–0.75, respectively. $E = E_0 + E_c$. The calibration of the neutral energy has a systematic error of 10%.

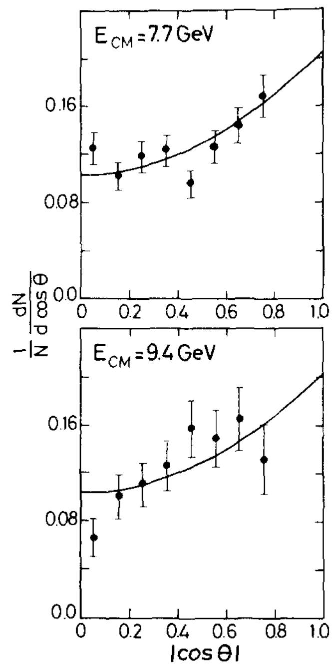

Fig. 3. The angular distribution $(1/N)(dN/d\cos\theta)$ of the thrust axis at 7.7 and 9.4 GeV.

the data are presented without correction for acceptance and cuts and compared to Monte Carlo results subject to the same analysis procedure.

In fig. 1 we show our results for the average visible sphericity $\langle S\rangle$ and $1-\langle T\rangle$ (where $\langle T\rangle$ is the average visible thrust) as functions of centre of mass energy together with the results from our Monte Carlo calculations. If we ignore the point of the upsilon, then both $\langle S\rangle$ and $1-\langle T\rangle$ show a very significant decrease as the centre of mass energy increases above 5 GeV. The change in $\langle S\rangle$ is in qualitative agreement with the results of the SLAC/LBL group who measured $\langle S\rangle$ at energies between 3 and 7.8 GeV [1,14]. The hatched region, corresponding to the isotropic Monte Carlo calculation, shows a gradual increase with energy. This is to be expected as the multiplicity is also increasing slowly with energy. We have checked that the change in the observed $\langle S\rangle$ or $1-\langle T\rangle$ is not limited to any particular multiplicity class; $\langle S\rangle$ and $1-\langle T\rangle$ measured for fixed multiplicities as functions of energy show approximately the same rate of decrease. The crosses in fig. 1 indicate the result of the jet model of Field and Feynman, the agreement is reasonable.

On the upsilon resonance both $\langle S\rangle$ and $1-\langle T\rangle$ show a dramatic change away from jet-like behaviour, compared to the data point just below the resonance at 9.4 GeV [‡4]. We have a small amount of data above the upsilon and we find that $\langle S\rangle$ and $1-\langle T\rangle$ do indeed decrease again to values compatible with those at 9.4 GeV (this is shown in the insets in fig. 1).

We have seen that thrust and sphericity produce very similar results on the average but it is also interes-

‡4 No attempt has been made to subtract the events from the continuum contribution to the data point on the upsilon resonance.

ting to ask how well the two methods agree in finding the jet axis. The distribution of the angle η between the thrust and sphericity axes at 9.4 GeV is shown in fig. 2a. The width of the peak at half height is about 15° and this gives an estimate of the uncertainty to be expected in any quantity calculated transverse to the jet axis (such as $\langle p_t \rangle$). The jet axis is also strongly correlated with the direction of the charged particle with the largest momentum. This can be seen from figs. 2b and 2c showing the distributions of angle between the largest momentum direction and the sphericity and thrust axes, respectively. We also note that the correlation is stronger for sphericity than for thrust as expected. We turn now to the question of the jet axis angular distribution. In general for unpolarised beams the jet axis angular distribution will be of the form

$$d\sigma/d\Omega \propto (1 + \alpha \cos^2\theta) \,, \qquad (4)$$

where θ is the polar angle with respect to the beam axis and α is a parameter which is equal to zero for spin-zero particles and equals one for spin-1/2 particles, neglecting the particle mass. We find from our Monte Carlo studies that we can measure $d\sigma/d\Omega$ for $|\cos\theta| < 0.8$ without significant loss of events. As any contamination from Bhabha scattering events will affect the determination of α, we have measured the forward–backward asymmetry of the signed $\cos\theta$ jet axis distribution, where the sign of the fastest charged particle is used. We find that the asymmetry is less than 2%.

Fig. 3 shows our results for the thrust axis angular distributions at centre of mass energies of 7.7 and 9.4 GeV. Acceptance loss has been corrected for using the jet Monte Carlo. The curve shown on each figure corresponds to a $1 + \cos^2\theta$ distribution. If we fit the angular distributions to the form (4) above then we find the following values for the parameter α, 0.76 ± 0.3 at 7.7 GeV and 1.63 ± 0.6 at 9.4 GeV. The azimuthal angular dependence of the jet axis is uniform at all energies and is consistent with no beam polarisation.

We consider next various properties of particles with respect to the jet axis. Although it is straightforward to calculate the observed $\langle p_t \rangle$ relative to the jet axis it is not quite obvious how this should be corrected to give a true measure of $\langle p_t \rangle$ for all particles in a jet. We have investigated this point using the jet Monte Carlo at 9.4 GeV. First we measure p_t relative to the genuine jet axis using all particles, which gives 300

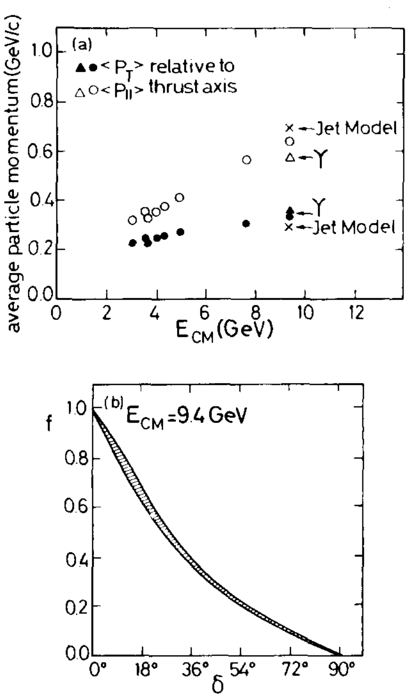

Fig. 4. (a) $\langle p_t \rangle$ and $\langle p_\parallel \rangle$ with respect to the thrust axis as functions of centre of mass energy. The crosses show the results from the jet Monte Carlo based on ref. [6]. (b) The average fraction of visible energy (f) outside a cone of fixed half angle δ as a function of δ at 9.4 GeV.

MeV/c, then relative to the sphericity axis with all particles, which gives 290 MeV/c, and finally by simulating the full detector acceptance and cuts and using only charged particles, which gives 284 MeV/c.

We feel that the change in $\langle p_t \rangle$ is small enough for us to show our results without correction. In fig. 4a we show $\langle p_t \rangle$ and $\langle p_\parallel \rangle$ relative to the thrust jet axis as functions of energy. The increase in $\langle p_t \rangle$ at low energies reflects that seen in $\langle p_\parallel \rangle$ and appears largely kinematic in origin.

At higher energies the change in $\langle p_t \rangle$ is much less than the corresponding change in $\langle p_\parallel \rangle$. Similar results are obtained if we use the sphericity method to determine the jet axis, but in this case the values of $\langle p_t \rangle$ are about 20 MeV/c smaller. This is not surprising as the sphericity method minimises Σp_t^2 whereas the thrust axis is chosen to maximise $\Sigma |p_\parallel|$. The crosses in fig. 4a show the results from the jet Monte Carlo. The difference in $\langle p_\parallel \rangle$ reflects the fact that our inclusive momentum spectrum has a more rapid decrease than the input data used in ref. [6].

From $\langle p_t \rangle$ and $\langle p_{\|} \rangle$ we can get a very crude estimate for the average opening angle of charged particles in a jet. For example at 5 GeV we find 33° for the half opening angle and at 9.4 GeV the result is 28°. These are quite large. To investigate this point further we have divided the events at 9.4 GeV into three thrust bins (0.5–0.75, 0.75–0.85, 0.85–1.0). For each bin we have used the charged particle energy to calculate $dE^c/d\lambda$, where $\lambda = \arccos(\hat{i}_{\rm jet} \cdot \hat{i}_{\rm charged})$. The results are shown as the histograms in figs. 2d–f. We find that $dE^c/d\lambda$ is strongly correlated with thrust, the distributions become broader as the events become less jetlike. The mean values for the bins of decreasing thrust are $21° \pm 1°$, $32° \pm 1°$ and $42° \pm 2°$.

An interesting question that has not been answered up to now, is, does the neutral energy follow the jet direction given by the charged particles and if so, how well? We are able to make a preliminary investigation of this point at 9.4 GeV. The data points in figs. 2d–f show the angular distributions of neutral energy with respect to the thrust axis $dE^0/d\lambda$ where now $\lambda = \arccos(\hat{i}_{\rm jet} \cdot \hat{i}_{\rm neutral})$ [‡5]. We see that the neutral energy is indeed well correlated with the charged jet axis direction for the bins with the most jet like events. The mean values for the neutral energy distributions are $31° \pm 1°$, $36° \pm 1°$ and $47° \pm 2°$ for bins of decreasing thrust. The ratios of neutral to charged energy for the bins of decreasing thrust are 0.73, 0.8 and 0.84, respectively.

From the results shown in figs. 2d–f we can see that the picture of jet behaviour obtained using charged particle information only will not be changed drastically when neutral energy information is included.

If we add the charged and neutral energy seen in the detector together we see about 85% of the centre of mass energy. Using this total energy information we have investigated the average fraction of the visible energy (f) outside a cone of fixed half angle δ. δ is varied from 0 where $f = 1$ to 90° where $f = 0$. The dominant source of error in calculating f for a given δ is the error in finding the true jet axis. To estimate this effect we have performed the analysis using both the sphericity and thrust methods. The result for f as a function of δ is shown as the broad hatched curve in fig. 4b. The width of the curve reflects the difference between the sphericity and thrust axes. It is clear that the jets we observe at 9.4 GeV are not yet very narrow, in agreement with the widths obtained from $\langle p_t \rangle$ and $\langle p_{\|} \rangle$ and $dE/d\lambda$ above.

[‡5] The PLUTO shower counter systems [8b] are constructed in 12° azimuthal sectors and provide a further coordinate to enable the polar angle θ to be determined in the range $-0.85 < \cos\theta < 0.85$.

To summarise, using the PLUTO detector we have studied the sphericity and thrust measures of jet production in e^+e^- annihilation into hadrons at centre of mass energies in the range 3.1 to 9.5 GeV. We confirm the existence of jets in this reaction and that the events become more jet-like as the energy increases. We see a striking change in mean sphericity and mean thrust on the upsilon resonance. We find that the jet axis angular distribution off resonance is consistent with that expected from a spin-1/2 particle origin. The quark fragmentation model of Feynman and Field gives a satisfactory description of our results for sphericity and thrust at 9.4 GeV. Finally we have demonstrated that neutral energy is correlated with the charged jet axis, with a characteristic width comparable to that found for charged particles.

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