≈ 3 GeV. The Stanford Linear Accelerator Laboratory results of $e^+e^- \rightarrow l^+l^-$ + missing energy can be explained as e', $\bar{e}'$ production followed by decays to $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$, or their antiparticles. The ν_e' would be absolutely stable and escape detection. The decay of the ν_μ' requires a mixing of either ν_μ' or μ' with lighter leptons.

The charmed quark c will decay preferably to the p quark through the enhanced J^+J^- interaction. Leptonic decays of the $\bar{c}n$ can then account for the dileptonic events seen at FNAL. The heavy pseudoscalars $\bar{\lambda}'n$, $\bar{c}'c$, etc., will decay via the enhanced J^+J^- to other heavy mesons. The $p'\bar{n}$, $n'\bar{n}$, etc., decay via the weaker interactions such as J^1J^3, J^2J^3 or J^1K^3, J^2K^3. The model also in general predicts CP nonconservation by virture of the fact that J^1, J^3 are CP even while J^2 is CP odd, so that terms linear in J^2 do not conserve CP. This point will be discussed in a longer paper under preparation.

*Research supported in part by National Science Foundation No. GP-4366-2X.

[1]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[3]A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 35, 69 (1975).

[4]R. N. Mohapatra, Phys. Rev. D 6, 2023 (1972).

[5]J. C. Pati and Abdus Salam, to be published; J. C. Pati, Abdus Salam, and J. Strathdee, Nuovo Cimento 26, 72 (1975); R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2588 (1975).

[6]H. S. Gurr, F. Reines, and H. W. Sobel, Phys. Rev. Lett. 28, 1406 (1972).

[7]W. Y. Lee, Colloq. Int. CNRS 245, 205 (1975).

[8]B. Aubert *et al.*, Phys. Rev. Lett. 32, 1457 (1974).

[9]F. J. Hasert *et al.*, Nucl. Phys. B73, 1 (1974).

[10]M. Perl, SLAC Report No. SLAC-PUB-1626 (unpublished).

[11]M. R. Krishnaswamy *et al.*, Phys. Lett. 57B, 105 (1975).

Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation*

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(Received 8 October 1975)

We have found evidence for jet structure in $e^+e^- \rightarrow$ hadrons at center-of-mass energies of 6.2 and 7.4 GeV. At 7.4 GeV the jet-axis angular distribution integrated over azimuthal angle was determined to be proportional to $1+(0.78\pm0.12)\cos^2\theta$.

In quark-parton constituent models of elementary particles, hadron production in e^+e^- annihilation reactions proceeds through the annihilation of the e^+ and e^- into a virtual photon which subsequently produces a quark-parton pair, each member of which decays into hadrons. At sufficiently high energy the limited transverse-momentum distribution of the hadrons with respect to the original parton production direction, characteristic of all strong interactions, results in oppositely directed jets of hadrons.[1-4] The spins of the constituents can, in principle, be determined from the angular distribution of the jets. In this Letter we report the evidence for the existence of jets and the angular distribution of the jet axis.

The data were taken with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at the SPEAR storage ring of the Stanford Linear Accelerator Center. Hadron production, muon pair production, and Bhabha scattering data were recorded simultaneously. The detector and the selection of events have been described previously.[5,6] The detector subtended $0.65\times4\pi$ sr with full acceptance in azimuthal angle and acceptance in polar angle from

50° to 130°. We have used the large blocks of data at center-of-mass energies ($E_{\rm c.m.}$) of 3.0, 3.8, 4.8, 6.2, and 7.4 GeV. We included only those hadronic events in which three or more particles were detected in order to avoid background contamination in events with only two charged tracks due to beam-gas interactions and photon-photon processes.

To search for jets we find for each event that direction which minimizes the sum of squares of transverse momenta.[7] For each event we calculate the tensor

$$T^{\alpha\beta}=\sum_i(\delta^{\alpha\beta}\vec{p}_i^{\,2}-p_i^{\alpha}p_i^{\beta}), \qquad (1)$$

where the summation is over all detected particles and α and β refer to the three spatial components of each particle momentum $\vec{p}_i$. We diagonalize $T^{\alpha\beta}$ to obtain the eigenvalues λ_1, λ_2, and λ_3 which are the sums of squares of transverse momenta with respect to the three eigenvector directions. The smallest eigenvalue (λ_3) is the minimum sum of squares of transverse momenta. The eigenvector associated with λ_3 is defined to be the reconstructed jet axis. In order to determine how jetlike an event is, we calculate a quantity which we call the sphericity (S):

$$S=\frac{3\lambda_3}{\lambda_1+\lambda_2+\lambda_3}=\frac{3(\sum_i p_{\perp i}^{\,2})_{\rm min}}{2\sum_i \vec{p}_i^{\,2}}. \qquad (2)$$

S approaches 0 for events with bounded transverse momenta and approaches 1 for events with large multiplicity and isotropic phase-space particle distributions.

The data at each energy were compared to Monte Carlo simulations which were based on either an isotropic phase-space (PS) model or a jet model. In both models only pions (charged and neutral) were produced. The total multiplicity was given by a Poisson distribution. The jet model modified phase space according to the square of a matrix element of the form

$$M^2=\exp(-\textstyle\sum_i p_{\perp i}^{\,2}/2b^2), \qquad (3)$$

where $p_\perp$ is the momentum perpendicular to the jet axis.

The angular distribution for the jet axis is expected to have the form

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

where θ is the polar angle of the jet axis with respect to the incident positron direction, φ is the azimuthal angle with respect to the plane of the storage ring, $\alpha=(\sigma_T-\sigma_L)/(\sigma_T+\sigma_L)$ with σ_T and σ_L the transverse and longitudinal production cross sections, and P is the polarization of each beam. (The polarization term will be discussed later.) The angular distribution given by Eq. (4) was used in the jet-model simulation. The simulations included the geometric acceptance, the trigger efficiency, and all other known characteristics of the detector. The total multiplicity and the charged-neutral multiplicity ratio for both models were obtained by fitting to the observed charged-particle mean multiplicity and mean momentum at each energy. In the jet model the parameter b was determined by fitting to the observed mean S at the highest energy (7.4 GeV). For lower energies the value of b was determined by requiring that the mean $p_\perp$ in the jet model be the same (315 MeV/c) as at 7.4 GeV.

Figure 1 shows the observed mean S and the model predictions. Both models are consistent with the data in the 3–4-GeV region. At higher energies the data have significantly lower mean S than the PS model and agree with the jet model. Figure 2 shows the S distributions at several energies. At 3.0 GeV the data agree with either the PS or the jet model [Fig. 2(a)]. At 6.2 and 7.4 GeV the data are peaked toward low S, favoring

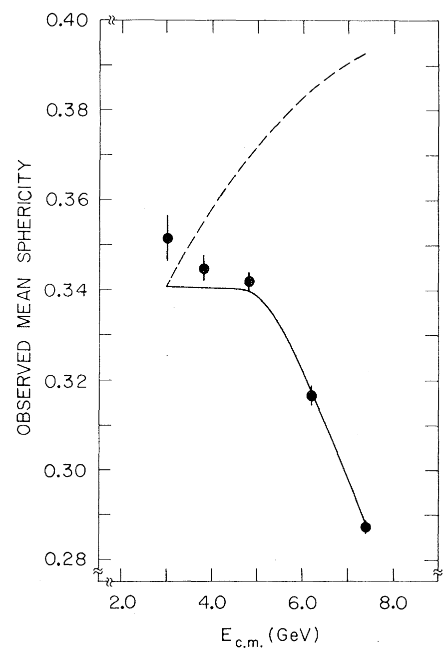

FIG. 1. Observed mean sphericity versus center-of-mass energy $E_{\rm c.m.}$ for data, jet model with $\langle p_\perp\rangle$ = 315 MeV/c (solid curve), and phase-space model (dashed curve).

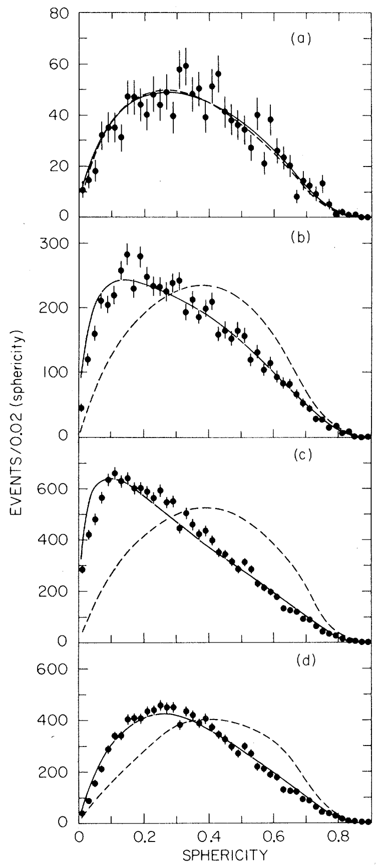

FIG. 2. Observed sphericity distributions for data, jet model with $\langle p_\perp \rangle = 315$ MeV/c (solid curves), and phase-space model (dashed curves) for (a) $E_{c.m.} = 3.0$ GeV; (b) $E_{c.m.} = 6.2$ GeV; (c) $E_{c.m.} = 7.4$ GeV; and (d) $E_{c.m.} = 7.4$ GeV, events with largest $x < 0.4$. The distributions for the Monte Carlo models are normalized to the number of events in the data.

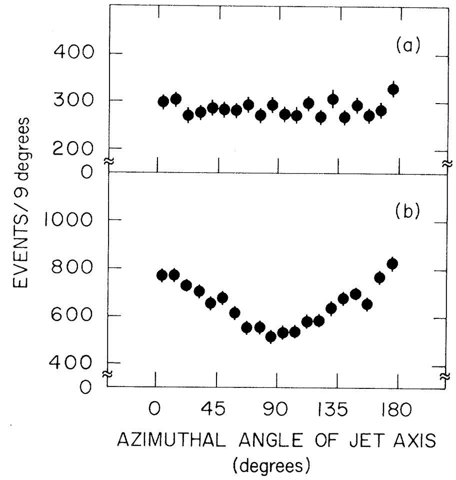

FIG. 3. Observed distributions of jet-axis azimuthal angles from the plane of the storage ring for jet axes with $|\cos\theta| \leq 0.6$ for (a) $E_{c.m.} = 6.2$ GeV and (b) $E_{c.m.} = 7.4$ GeV.

the jet model [Figs. 2(b) and 2(c)]. At the highest two energies, the PS model poorly reproduces the single-particle momentum spectra, having fewer particles with $x > 0.4$ ($x = 2p/E_{c.m.}$ and p is the particle momentum) than the data.[8] The jet-model x distributions are in better agreement. For $x < 0.4$ the x distributions for both models agree with the data. Therefore, we show in Fig. 2(d) the S distributions at 7.4 GeV for those events in which *no* particle has $x > 0.4$. The jet model is still preferred.

At $E_{c.m.} = 7.4$ GeV the electron and positron beams in the SPEAR ring are transversely polarized, and the hadron inclusive distributions show an azimuthal asymmetry.[9] The φ distributions of the jet axis for jet axes with $|\cos\theta| \leq 0.6$ are shown in Fig. 3 for 6.2 and 7.4 GeV.[10] At 6.2 GeV, the beams are unpolarized[9] and the φ distribution is flat, as expected. At 7.4 GeV, the φ distribution of the jet axis shows an asymmetry with maxima and minima at the same values of φ as for $e^+e^- \to \mu^+\mu^-$.

The φ distribution shown in Fig. 3(b) and the value for P^2 (0.47 ± 0.05) measured simultaneously by the reaction[9] $e^+e^- \to \mu^+\mu^-$ were used to determine the parameter α of Eq. (4). The value obtained for the *observed* jet axis is $\alpha = 0.45 \pm 0.07$. This observed value of α will be less than the true value which describes the production of the jets because of the incomplete acceptance of the detector, the loss of neutral particles, and our method of reconstructing the jet axis. We have used the jet-model Monte Carlo simulation to estimate the ratio of observed to produced values of α and find this ratio to be 0.58 at 74 GeV. Thus the value of α describing the *produced* jet-axis angular distribution is $\alpha = 0.78 \pm 0.12$ at $E_{c.m.} = 7.4$ GeV. The error in α is statistical only; we estimate that the systematic errors in the observed α can be neglected. However, we have not studied the model dependence of the correction factor relating observed to produced values of α.

The sphericity and the value of α as determined above are properties of whole events. The simple jet model used for the sphericity analysis can also be used to predict the single-particle inclusive angular distributions for all values of the secondary particle momentum. In Fig.

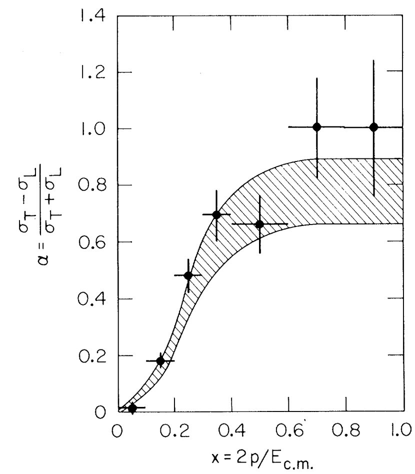

FIG. 4. Observed inclusive α versus x (from Ref. 9) for particles with $|\cos\theta| \leq 0.6$ in hadronic events at $E_{c.m.} = 7.4$ GeV. The prediction of the jet-model Monte Carlo simulation for jet-axis angular distribution with $\alpha = 0.78 \pm 0.12$ is represented by the shaded band.

4 values for the inclusive hadron α as a function of x at 7.4 GeV[9] are compared with the jet-model calculation. The model assumed the value $\alpha = 0.78 \pm 0.12$ for the jet-axis angular distribution. The prediction agrees well with the data for all values of x.

We conclude that the data strongly support the jet hypothesis for hadron production in e^+e^- annihilation. The data show a decreasing mean sphericity with increasing $E_{c.m.}$ and the sphericity distributions peak more strongly at low values as $E_{c.m.}$ increases. Both of these trends agree with a jet model and disagree with an isotropic PS model. The mean transverse momentum relative to the jet axis obtained using the jet-model Monte Carlo simulation was found to be 315 ± 2 MeV/c. At $E_{c.m.} = 7.4$ GeV the coefficient α for the jet-axis angular distribution in Eq. (4) has been found to be nearly $+1$ giving a value for σ_L/σ_T of 0.13 ± 0.07. The jet model also reproduces well the inclusive hadron α versus x. All of this indicates not only that there are jets but also that the helicity along the jet axis is ± 1. In the framework of the quark-parton model, the partons must must have spin $\frac{1}{2}$ rather than spin 0.

*Work supported by the U. S. Energy Research and Development Administration.

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[1]S. D. Drell, D. J. Levy, and T. M. Yan, Phys. Rev. 187, 2159 (1969), and Phys. Rev. D 1, 1617 (1970).

[2]N. Cabibbo, G. Parisi, and M. Testa, Lett. Nuovo Cimento 4, 35 (1970).

[3]J. D. Bjorken and S. J. Brodsky, Phys. Rev. D 1, 1416 (1970).

[4]R. P. Feymann, *Photon-Hadron Interactions* (Benjamin, Reading, Mass., 1972), p. 166.

[5]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[6]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[7]It is impossible to determine the jet axis exactly, even with perfect detection efficiency; the method described here, which was suggested in Ref. 3, is the best approximation known to us.

[8]The momentum distributions will be discussed in a subsequent paper.

[9]R. F. Schwitters *et al.*, Phys. Rev. Lett. 35, 1320 (1975).

[10]Since the jet axis is a symmetry axis, the azimuthal angle $\varphi + 180°$ is equivalent to the azimuthal angle φ.