Tests of Models for Parton Fragmentation by Means of Three-Jet Events in e^+e^- Annihilation at $\sqrt{s} = 29$ GeV

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The distribution of particles in three-jet events is compared with the predictions of three fragmentation models currently in use: the Lund string model, the Webber cluster model, and an independent fragmentation model. The Lund model and, to a certain extent, the Webber model provide reasonable descriptions of the data. The independent fragmentation model does not describe the distribution of particles at large angles with respect to the jet axes. The results provide evidence that the sources of hadrons are Lorentz boosted with respect to the overall c.m.

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The fragmentation of systems of partons (quarks and gluons) into observed hadrons is described, at short distances, by perturbative quantum chromodynamics (QCD), while the long-distance behavior cannot at present be calculated. Many phenomenological models exist which attempt to describe the experimental data. An important question, and one which differentiates models, is whether the observed hadrons originate from sources which are Lorentz boosted relative to the overall event center of mass (i.e., sources such as moving string segments or clusters). The three-jet event sample in e^+e^- annihilations—where the three jets presumably originate from a quark, an antiquark, and a gluon—constitutes a particularly simple and sensitive area to search for such effects. It should be noted that within the event plane defined by the three final-state jets it is the region between the jets, not the jets themselves, which are most sensitive to this question of reference-frame differences between models.

In this paper, we study the detailed structure of three-jet events in e^+e^- annihilations at a center-of-mass energy of 29 GeV, using data collected by the time projection chamber (TPC) detector at PEP. We compare three models with different Lorentz-boosted structures for the fragmentation process: independent fragmentation models (IF), string fragmentation models (SF), and QCD cluster fragmentation models (CF). Previously, the JADE collaboration at PETRA found a preference for SF over IF models[1]; however, there has been no confirmation of their results until now. Here, we extend the analysis to the current generation of IF, SF, and CF models. We use the superior particle-identification capabilities of the TPC to compare the signals from heavy hadrons (kaons, protons, and lambdas) with those from pions.

In IF models,[2] each parton fragments into a jet of hadrons independently of the other partons and in an azimuthally symmetric manner as observed from the overall center of mass. Thus in three-jet events, all three regions between jets are populated by the same mechanism, namely the momentum distribution transverse to the jet axes [Fig. 1(a)].

In SF models, the force field binding the partons is represented by a confined narrow tube or "string." The Lund SF model[3] predicts that in a three-jet event this string stretches from the quark to the antiquark through the gluon [Fig. 1(b)]. The hadron sources (i.e., the qg and $\bar{q}g$ string segments) each fragment in their respective rest frames. Fragmentation products thus receive a Lorentz boost as observed from the overall center of mass. As a result of this boost, hadrons populate the qg and the $\bar{q}g$ regions. The $q\bar{q}$ region is comparatively depleted; a hadron populates this region only when it has enough transverse momentum to "cross over" from the qg or $\bar{q}g$ segments.

In CF models,[4,5] the partons created by the e^+e^- annihilation initiate a quark-gluon shower described by

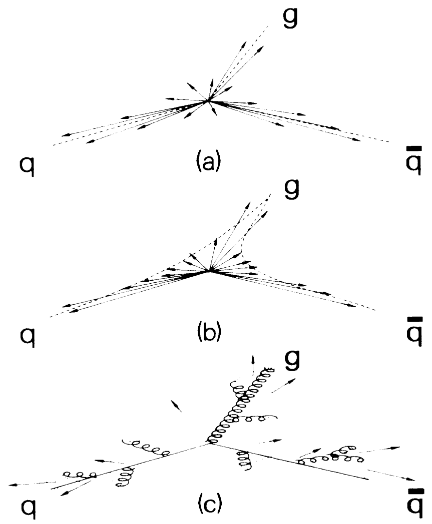

FIG. 1. Three-jet event structure for (a) IF, (b) SF, and (c) CF models. The arrows in (a) and (b) indicate the momentum-space distribution of particles. The dashed lines in (a) represent the parton directions, those in (b) the strings stretched between partons. (c) shows the CF parton shower (solid and curly lines) and clusters (dotted ellipses). The motion of the clusters is indicated by arrows; in CF models demonstrating a boost signal (see text), the resulting momentum-space distribution of particles is similar to that in (b).

leading-log QCD. Each parton in the shower evolves until its virtual mass drops below a cutoff $Q_0 \sim 1-5$ GeV. The color structure of the shower defines a series of color-neutral clusters which decay into hadrons according to two-body phase space or a parametrization of low-energy data. In this analysis, we examine the Webber CF model.[4] The Webber model includes the leading effects of soft-gluon interference; as a consequence the parton emission angles are ordered such that each successive angle is smaller than the preceding one. This ordering causes the moving hadron sources (clusters) to populate preferentially the qg and $\bar{q}g$ regions rather than the $q\bar{q}$ region. (Briefly, this is because the angular ordering causes partons to align along the jet axes whereas the $q\bar{q}$ region corresponds to the largest angle between jets: The central section of this region is thus the farthest from the jet axes.) Each cluster decays in its own rest frame, producing a "boost signal" similar to that of the SF model [Fig. 1(c)].

We examine three aspects of the data to search for effects of boosted hadron sources. (1) The angular particle density in three-jet events is compared to the model predictions. (2) The ratios of particle population in the regions between the jets are studied. This is an especially useful technique since many systematic effects both in the experiment (e.g., acceptance effects) and in the modeling (e.g., details of the transverse momentum distribution) cancel, to first order. (3) Since the effects predicted for the SF and CF models arise from Lorentz boosts of the hadrons, the signals expected in (1) and (2) for these models are enhanced by studying particles of large mass or large p_{out}, the momentum component out of the event plane. This is because such particles have a large energy compared to the momentum component along the boost direction and thus receive larger modifications to that momentum component when boosted to another frame. For tests (1)–(3), the IF and SF models are tuned to fit the global properties of the data. The CF model is not tuned as it lacks the exact three-jet matrix elements; we therefore use the default parameter values provided by the author.[4] We emphasize, however, that the ratios formed in test (2) are relatively insensitive to the model parameters and thus to this lack of tuning.

The data sample is based on 29 000 hadronic annihilation events recorded by the TPC collaboration at $\sqrt{s} = 29$ GeV, in 77 pb^{-1} of running at PEP. Detailed descriptions of the apparatus, its performance, and the criteria used to identify annihilation events have been provided elsewhere.[6] Charged-particle identification is accomplished through simultaneous dE/dx and momentum measurements. The accuracy of the dE/dx measurement is 3.7% and the momentum resolution is $(dp/p)^2 = (0.06)^2 + (0.035p)^2$, with p in GeV/c. Photon identification is provided by a barrel hexagonal calorimeter with an energy resolution of 16%/$[E(\text{GeV})]^{1/2}$.

A three-jet event sample is identified as follows. We calculate the sphericity eigenvalues Q_1, Q_2, and Q_3 ($Q_1 < Q_2 < Q_3$ and $Q_1 + Q_2 + Q_3 = 1$) and associated eigenvectors $\mathbf{q}_1$, $\mathbf{q}_2$, and $\mathbf{q}_3$, using charged particles and photons. Preliminary three-jet event candidates are selected by requiring $Q_1 < 0.06$ and $Q_2 - Q_1 > 0.05$. To eliminate events with portions of jets outside the detector, we require the polar angle of $\mathbf{q}_3$ to be greater than 40° and the total momentum imbalance $|\sum \mathbf{p}_i| / \sum |\mathbf{p}_i|$ to be less than 0.40. Surviving events are subjected to a jet-finding algorithm[7] which searches for three-jet structure and which requires each jet to have at least two particles and 1.5 GeV/c of momentum. The final three-jet sample contains 3022 events. Jet directions are specified by the vector sum of the particle momenta within the jet, after projection into the "event plane" defined by $\mathbf{q}_2$ and $\mathbf{q}_3$.

The jets are labeled 1, 2, and 3 such that jet 1 is opposite the smallest angle between jets and jet 3 is opposite the largest angle. The angle ϕ is defined within the event plane and proceeds from jet 1 ($\phi = 0°$) to jet 2 ($\phi \sim 155°$), then to jet 3 ($\phi \sim 230°$) and back to jet 1 ($\phi = 360°$). Studies using the IF and SF models indicate that about 80% of the sample consists of three-jet $q\bar{q}g$ events (the other 20% are two-jet or four-jet events) and that jets 1, 2, and 3 are the gluon jets in 7%, 8%, and 55% of the events, respectively.

Figure 2 shows the normalized particle density $(1/N)dN/d\phi$ for the three-jet events, along with the predictions of the three models, for all charged particles and photons [2(a)] and for particles with large p_{out} [2(b)] or mass [2(c)]. The solid curve is the SF model of Lund, version 5.2.[8] The dashed curve is an IF model provided by the Lund Monte Carlo program,[8] in which the gluon treatment is similar to that of the Hoyer independent-jet model.[2] The dotted curve is the Webber CF model, version 1.1,[4] using the default parameter values. The IF and SF models have been tuned to describe global properties of the data such as multiplicity, scaled momentum ($x_p = 2p/E_{c.m.}$), sphericity, thrust, and the overall momentum distributions in and out of the event plane. All model predictions include full detector simulation.

As seen in Fig. 2, the highest particle density occurs in the jet-1 peak and the lowest in the jet-(1–2) valley. The ratio of these densities is 20:1, 25:1, and 50:1, respectively, for Figs. 2(a), 2(b), and 2(c). The SF model provides a reasonable description of this variation and of the entire ϕ range. The IF model provides nearly as good a description. However, the IF model overpredicts the density of the 1–2 valley in Fig. 2(a) by about 30%. This discrepancy is increased for particles with large p_{out} and mass: The IF model overpredicts the 1–2 valley density by a factor of 2 in both Figs. 2(b) and 2(c). We have verified that this discrepancy is not related to the particular gluon modeling scheme by testing variants of the IF model. These variants treat the gluon as an ordinary quark, as a quark with transverse width 50% higher than an ordinary quark, as a quark-antiquark pair sharing momentum according to the Altarelli-Parisi splitting function, and as a Lund gluon. Our results are also insensitive to the algorithm used to conserve energy and momentum in the IF events (i.e., maintain parton directions or parton energies), relevant because IF models intrinsically cannot conserve both of these simultaneously. We have further ascertained that the IF model cannot be tuned to fit the 1–2 valley and simultaneously provide reasonable fits of the global event distributions. For the CF model, the predictions of Fig. 2 are generally too large for all the regions between jets; however, this result is sensitive to the CF model parameters and thus can perhaps be explained by the lack of tuning.

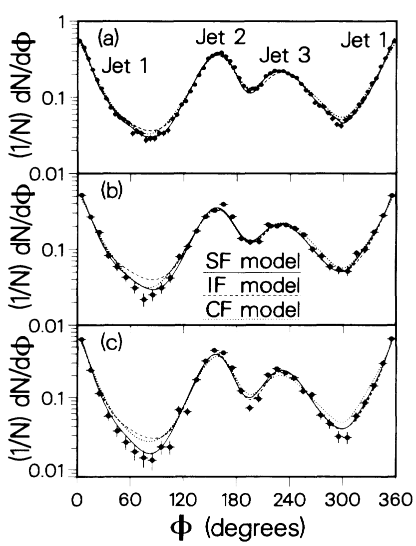

FIG. 2. Particle density $(1/N)dN/d\phi$ in three-jet events for (a) all charged particles and photons, (b) those charged particles and photons satisfying $0.3 < p_{out} < 0.5$ GeV, and (c) a heavy-particle sample (with about 80% purity) of charged and neutral kaons, protons, and lambdas. Also shown are the predictions of the IF, SF, and CF models.

To perform the comparison of the particle populations in the valleys, we calculate the normalized particle population $\mathcal{N}_{ij}$.[1] For each particle between jets i and j, after projection into the event plane, we divide the angle between jet i and the particle by the angle between jets i and j. $\mathcal{N}_{ij}$ is the number of particles between 0.3 and 0.7 in this normalized angular region—the region most sensitive to boost effects. The comparison of the 1–2 and 1–3 valleys is made with the ratio $\mathcal{N}_{31}/\mathcal{N}_{12}$. We have verified that $\mathcal{N}_{31}/\mathcal{N}_{12}$ is insensitive to the variants of the IF model discussed in connection with Fig. 2, to details of the tuning of the IF or CF models, and to the detector acceptance. For IF models, we expect $\mathcal{N}_{31}/\mathcal{N}_{12} \sim 1$ independent of the particle mass or p_{out}, while for models with boosted hadron sources (SF and CF), we expect this ratio to be greater than 1 and to increase in magnitude as mass and p_{out} increase.

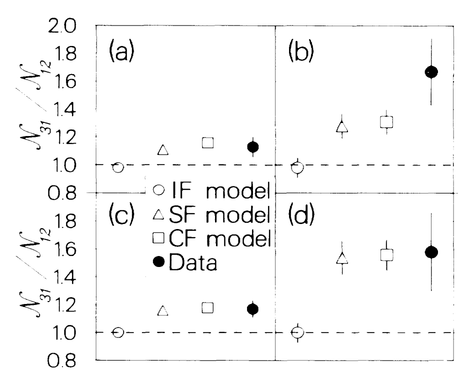

FIG. 3. The ratio $\mathcal{N}_{31}/\mathcal{N}_{12}$ of the population between jets, for the data and models. (a),(b) $\mathcal{N}_{31}/\mathcal{N}_{12}$ for charged pions in two intervals of p_{out}: (a) $0.0 < p_{out} < 0.2$ GeV and (b) $0.3 < p_{out} < 0.5$ GeV. (c) $\mathcal{N}_{31}/\mathcal{N}_{12}$ for all charged pions. (d) This ratio for the heavy-particle sample of Fig. 2(c).

The ratio $\mathcal{N}_{31}/\mathcal{N}_{12}$ is shown in Fig. 3 for the data and models. The data demonstrate that $\mathcal{N}_{31}/\mathcal{N}_{12}$ is significantly greater than 1 and that it increases in magnitude as mass and $p_{\rm out}$ increase. The SF and CF models provide good descriptions of the overall level of the signal and of the mass and $p_{\rm out}$ behavior. In contrast, the IF model predicts a value of this ratio consistent with 1 and shows no mass or $p_{\rm out}$ dependence.

In summary, we have studied the angular distribution in the event plane of particles produced in the three-jet events of e^+e^- annihilation. The particle densities vary by factors of 20–50 between the peaks and valleys of these distributions. In general, the models studied reproduce these large variations, with the exception of the extreme minima between jets, the regions most sensitive to boost effects. Within our statistical precision, all three of our techniques (absolute three-jet particle density, $\mathcal{N}_{31}/\mathcal{N}_{12}$ population ratios, and the mass and $p_{\rm out}$ dependence) provide evidence for boosted hadron sources, as exemplified by the Lund string-fragmentation or Webber cluster-fragmentation models. In contrast, there seems to be no feasible way to reproduce the data with independent fragmentation modeling.

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