Title
TESTS OF MODELS FOR PARTON FRAGMENTATION USING 3-JET EVENTS IN $e^+e^-$ ANNIHILATION /$s = 29$ GeV

Permalink
https://escholarship.org/uc/item/2dx217f0

Author
Aihara, H.

Publication Date
1984-10-01
Tests of Models for Parton Fragmentation Using 3-Jet Events in $e^+e^-$ Annihilation $\sqrt{s} = 29$ GeV

PEP-4 TPC Collaboration

October 1984
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Tests of Models for Parton Fragmentation using 3-jet Events in $e^+e^-$ Annihilation $\sqrt{s} = 29$ GeV*


1Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720,
2University of California, Los Angeles, CA 90024,
3University of California, Riverside, CA 92521,
4Johns Hopkins University, Baltimore, MD 21218,
5University of Massachusetts, Amherst, MA 01003,
6University of Tokyo, Tokyo 113, JAPAN

October 1984

*This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
Abstract

The distribution of particles in 3-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 (IF). The Lund model and, to a certain extent, the Webber model provide reasonable descriptions of the data. The IF 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.

PACS number: 13.65.+i
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 3-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 3-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, using 1st order QCD \(^1\); however, there has been no confirmation of their results until now. Here, we extend the analysis to 2nd order QCD and to CF models. We use the superior particle identification capabilities of the TPC to compare the signals from heavy hadrons (kaons, protons, lambdas) with those from pions.
In IF models, 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 3-jet events, all three regions between jets are populated by the same mechanism, namely the momentum distribution transverse to the jet axes (Figure 1(a)).

In SF models, the force field binding the partons is represented by a confined narrow tube or “string”. The Lund SF model predicts that in a 3-jet event this string stretches from the quark to the antiquark through the gluon (Figure 1(b)). The hadron sources (i.e., the $qg$ and $\bar{q}g$ string segments) each fragment in their respective rest frame. 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, the partons created by the $e^+e^-$ annihilation initiate a quark-gluon shower described by 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 2-body phase space or a parameterization of low energy data. In this analysis, we examine the Webber CF model. 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 preferentially populate 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 (Figure 1(c)).

We examine three aspects of the data to search for effects of boosted hadron sources. (1) The angular particle density in 3-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 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 3-jet matrix elements: we therefore use the default parameter values provided by the author. 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 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. 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 \(16%/\sqrt{E(\text{GeV})}\).

A 3-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 \(\vec{q}_1, \vec{q}_2\) and \(\vec{q}_3\), using charged particles and photons. Preliminary 3-jet event candidates are selected by requiring \(Q_1 < .06\) and \(Q_2 - Q_1 > .05\). To eliminate events with portions of jets outside the detector, we require the polar angle of \(\vec{q}_3\) to be greater than 40 degrees and the total momentum imbalance \(|\sum \vec{p}_i| / \sum |\vec{p}_i|\) to be less than 0.40. Surviving events are subjected to a jet-finding algorithm which searches for 3-jet structure and which requires each jet to have at least 2 particles and \(1.5\) GeV/c of momentum. The final 3-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 \(\vec{q}_2\) and \(\vec{q}_3\).

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 \(\phi\) is defined within the event plane and proceeds from jet 1 \((\phi = 0^\circ)\) to jet 2 \((\phi \sim 155^\circ)\), then to jet 3 \((\phi \sim 230^\circ)\) and back to jet 1 \((\phi = 360^\circ)\). Studies using the IF and SF models indicate that about 80% of the sample consists of 3-jet \(q\bar{q}g\) events (the other 20% are 2-jet or 4-jet events) and that jet 1, 2 and 3 is the gluon jet in 7, 18 and 55% of the events, respectively.

Figure 2 shows the normalized particle density \((1/N)dN/d\phi\) for the 3-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. The dashed curve is an IF model provided by the Lund Monte Carlo program, in which the gluon treatment is similar to that of the Hoyer independent jet model. The dotted curve is the Webber CF model, Version 1.1, 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 Figure 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 Figures 2(a), 2(b) and 2(c). The SF model provides a reasonable description of this variation and of the entire $\phi$ range. The IF model provides nearly as good a description. However, the IF model over-predicts the density of the 1-2 valley in Figure 2(a) by about 30%. This discrepancy is increased for particles with large $p_{out}$ and mass: the IF model over-predicts the 1-2 valley density by a factor of 2 in both Figures 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 Figure 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.

To perform the comparison of the particle populations in the valleys, we calculate the normalized particle population $N_{ij}$. 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. $N_{ij}$ is the number of particles between .3 and .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 $N_{31}/N_{12}$. We have verified that $N_{31}/N_{12}$ is insensitive to the variants of the IF model discussed in connection with Figure 2, to details of the tuning of the IF or CF models and to the detector acceptance. For IF models, we expect $N_{31}/N_{12} \sim 1$ 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.

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

In summary, we have studied the angular distribution in the event plane of
particles produced in the 3-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 3-jet particle density, $N_{31}/N_{12}$ population ratios, and the mass and $p_{out}$ 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.

We acknowledge the efforts of the PEP staff, and the engineers, programmers and technicians of the collaborating institutions who made this work possible. This work was supported by the Department of Energy under contracts DE-AC03-76SF00098, DE-AM03-76SF00034, and DE-AC02-76ER03330, the National Science Foundation and the Joint Japan-US Collaboration Program in High Energy Physics.
References


7. Our jet-finder is similar to that described in A. Bäcker, Z. Phys. C12, 161 (1982).

Figure Captions

Figure 1. 3-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).

Figure 2. Particle density $(1/N) dN/d\phi$ in 3-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.

Figure 3. The ratio $N_1/N_{12}$ of the populations between jets, for the data and models. (a) and (b) show $N_1/N_{12}$ for charged pions in two intervals of $p_{out}$: $0.0 < p_{out} < 0.2$ GeV (a) and $0.3 < p_{out} < 0.5$ GeV (b). (c) shows $N_1/N_{12}$ for all charged pions, (d) shows this ratio for the heavy particle sample of figure 2(c).
Figure 3
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.