COMPARISON OF THREE-JET EVENTS WITH QCD SHOWER MODELS

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Received 29 April 1985

Distributions of particles in three-jet events from $e^+e^- \to$ hadrons are compared with different fragmentation schemes, i.e. the Lund string model, independent parton fragmentation and QCD shower models. Effects specific to the string scheme, which have been seen in the data, are also reproduced by QCD shower models if soft gluon interference effects are included.

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Five years ago first evidence [1] was presented that three-jet events produced in e^+e^- annihilation are better described by the string model of the Lund group [2] than by independent fragmentation models [3,4]. In the meantime, this evidence has been further corroborated [5,6], and has recently also been confirmed by the TPC collaboration at PEP [7].

In the independent fragmentation models, the quarks and gluons from perturbative QCD calculations in first or second order of α_s, fragment independently of each other into jets of hadrons, which have limited transverse momentum with respect to the CMS momentum vectors of the original partons. In the Lund string model, the fragmentation proceeds in the boosted systems of the colour flux lines. Specific observable consequences of this scheme have been elaborated in our previous publications [1,5,6].

It has also been shown [8] that the string model not only provides a better description of the three-jet events, but also of the energy–energy correlations containing all multihadronic events. These observations have been confirmed by the MAC-collaboration [9].

In this letter we compare the data with QCD parton shower models. In these models introduced by Wolfram and Fox [10] and further developed by Field [11] and Gottschalk [12], the formation of the final-state hadrons is preceded by a succession of branching processes in which gluons and quarks are created in a cascade like manner, derived from QCD in leading log approximation. In the Gottschalk model, for instance, partons produced far off-mass shell in hard processes, evolve by successive branchings into jet-like cascades of partons closer to the mass shell. If $q_1^2, q_2^2, ..., q_i^2$ denote the virtual masses of the first, the second, ..., and the ith parton, then $q_1^2 > q_2^2 > ... > q_i^2 > ... > Q_0^2$, where Q_0^2 is the cut-off limit at which the cascade stops and each gluon splits nonperturbatively into $q\bar{q}$-pairs. In the final step, different $q\bar{q}$-pairs combine to colour singlet clusters, which decay into the final-state hadrons.

The leading log approximation was improved in recent theoretical studies on soft gluon interference [13]. These calculations take into account "leading" logarithms from collinear (mass) divergences and "subleading" logarithms from infrared (soft gluons) divergences. The coherent summation of these contributions leads to destructive interference effects ‡1. To interpret this in a semiclassical way, the ordering in "off-shellness" has to be replaced by an ordering of emission angles [15]. This leads to a suppression of the large angle emission of soft gluons. The ordering of gluon emission angles instead of the ordering of virtual masses is incorporated into the Webber model [15], which otherwise has a parton evolution similar to the model of Gottschalk. For further details see ref. [15].

In fig. 1 the energy–energy correlations and their asymmetry observed [8] in $e^+e^- \to$ hadrons at $\sqrt{s}$ =

‡1 The existence of analogue effects in QED [14] has been known since 1955.

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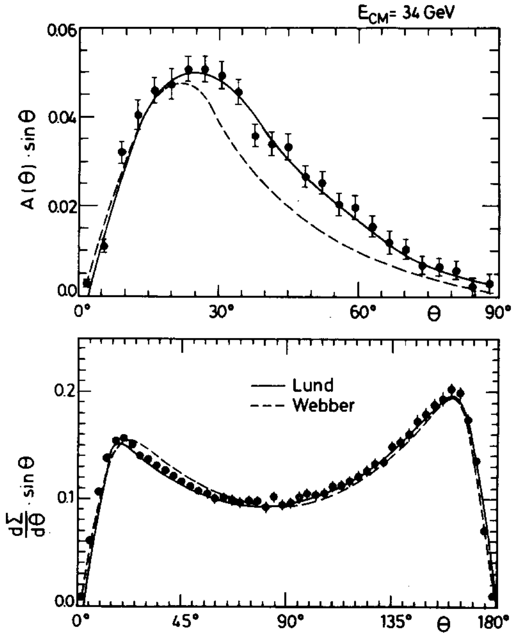

Fig. 1. The energy–energy correlations and their asymmetry together with the predictions of the Lund and Webber models. For details of the data and the Lund model see ref. [8].

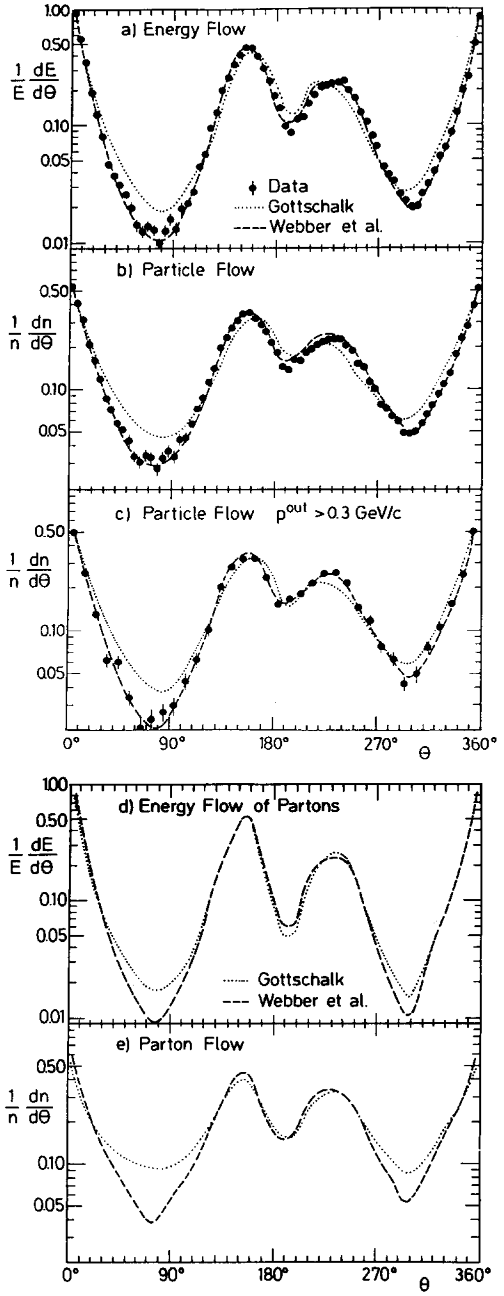

Fig. 2. (a) The energy flow $(1/E)\ \mathrm{d}E/\mathrm{d}\theta$ and (b) the particle flow $(1/n)\ \mathrm{d}n/\mathrm{d}\theta$ (E is the total energy, n the total number of particles contained in the plot) projected onto the event plane of the three-jet events. The corresponding predictions of the Gottschalk and the Webber model are also shown. (c) The particle flow for particles with a momentum component perpendicular to the event plane exceeding 300 MeV/c; (d) and (e) show the model predictions for the partons.

34 GeV are compared with the predictions of the Lund and the Webber models. The Webber model ‡2 does not reproduce in detail the experimental data. It predicts less events of three-jet structure than observed. This, however, is not unexpected since the QCD shower models do not contain the full three-parton matrix element.

Notwithstanding this deficiency it is instructive to study the particle distributions in three-jet events predicted by the QCD shower models. The topological distributions of the three-jet events are quite similar for the data and both the Lund and Webber models, if normalized to the same number of three-jet events. Fig. 2 shows the energy and the particle flow in the event plane of selected three-jet events ‡3 in comparison with two different QCD shower models. For these distributions all particles are projected onto the event plane, and the angle θ runs from the axis of jet #1 and via jets #2 and #3 back to #1. The jet ordering is chosen according to the angles between the jet axes: jet #1 is opposite the smallest and jet #3 opposite the largest angle. Interpreting these three jets in terms of gluon bremsstrahlung $e^+e^- \to q\bar{q}g$ one finds that jets #1 and #2 represent the fragments of quarks in the majority of the cases.

The Webber model does reproduce the data, whereas the Gottschalk model predicts too much energy and too many particles in the region between the jets. In the data the depletion between jets #1 and #2 increases with increasing p^{out}, the momentum component normal to the event plane. This is seen by comparing fig. 2b with fig. 2c, where the particle flow is drawn only for particles with $p^{out} > 0.3$ GeV/c. Although this p^{out} dependence is also indicated in the Gottschalk model, it only occurs in the Webber model with the strength required by the data.

In figs. 2d and 2e the analogous distributions predicted by the models for the partons at the end of the cascade, rather than for the hadrons are plotted. They exhibit similar differences between the Webber and Gottschalk models as predicted for the final hadrons, suggesting that these differences are not caused by

‡2 The following parameters were used for the Webber model: Λ_{QCD} = 250 MeV, Q_0^2 = 0.36 GeV, a maximum cluster mass M_f = 4 GeV, and masses of u, d and s quarks of 0.3, 0.3 and 0.5 GeV, respectively.

‡3 The selection criteria of planar three-jet events are given in refs. [5,6].

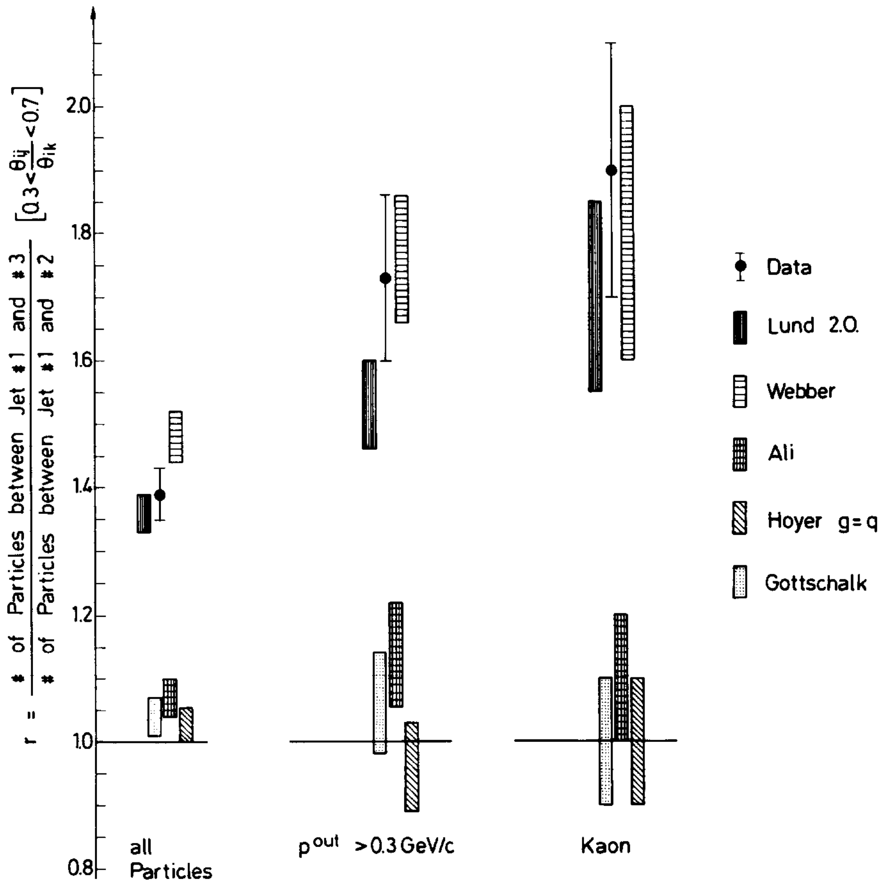

Fig. 3. The ratio of the number of particles in the angular range between jets #1 and #3 to the corresponding number between jets #1 and #2 for all particles, particles with $p^{out} > 0.3$ GeV/c and for a kaon enriched sample. The data are compared with the model predictions.

different treatment of the final decay of the clusters into hadrons, but by the difference in the QCD calculations.

To quantify the degree of depletion observed, which is usually referred to as string effect, the ratio r [1,5,6] of the number of particles in the region between jets #1 and #3 and between jets #1 and #2 is calculated. This ratio is shown in fig. 3, separately for all particles, particles with $p^{out} > 0.3$ GeV/c and for a particle sample containing about 50% kaons. The model predictions for r are displayed as well. Only the Lund and the Webber models provide a reasonable description of the data, whereas the independent fragmentation models and the Gottschalk model predict values for r close to unity.

The string effect although most prominent for the particles between the jets, is also apparent in the particle distributions within the jets. Whereas independent parton fragmentation predicts symmetric particle distributions about the jet axes, the string picture exhibits asymmetric distributions, which are also observed in the data [6]. Following ref. [6], we calculated for each particle in a jet the momentum component in the event plane transverse to the jet axis ($p_\perp^{in}$). The sign of $p_\perp^{in}$ is defined in the insert of fig. 4a. Fig. 4 shows the average $\langle p_\perp^{in} \rangle$ as a function of $p_\parallel$, the momentum component parallel to the jet axis. For high $p_\parallel$ the data of jet #1 and #2 point away

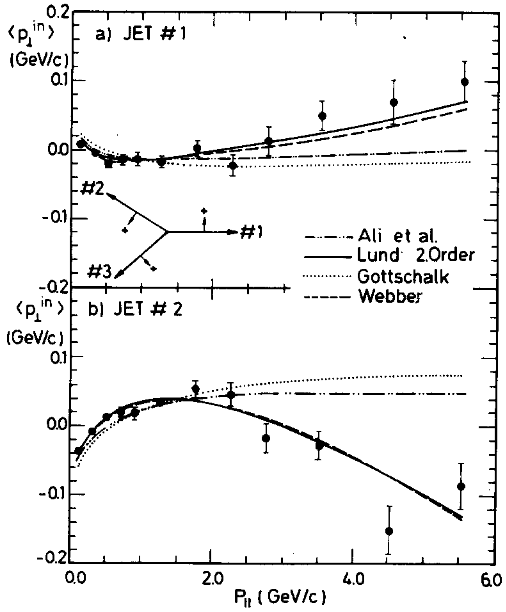

Fig. 4. The average transverse momentum component in the event plane with respect to the jet axis $\langle p_\perp^{in}\rangle$, as a function of the momentum component parallel to the jet axis $p_\parallel$, for charged and neutral particles of (a) jet #1 and (b) jet #2. The sign convention of $p_\perp^{in}$ is sketched in the insert. The predictions of different models are also shown.

from jet #3. This behaviour is reproduced by the Lund and the Webber models, but not by the other models shown in fig. 4.

A further point is the broadening of the gluon jet, which has been observed in the data [6,16]. Again the Lund model and the Webber model predict differences between quark and gluon jets of similar size in rough agreement with the experimental distributions, whereas the Gottschalk model results in a smaller effect. For further details we refer to ref. [17].

In summary, we have shown that experimental distributions which are particularly sensitive to the string effect, are also reproduced by QCD shower models in which soft gluon interference effects are taken into account.

We are indebted to the PETRA machine group and the group of the computer centre for their excellent support and to all the engineers and technicians of the collaborating institutions who have participated in the construction and maintenance of the apparatus. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Ministry of Education, Science and Culture of Japan, by the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory and by the US Department of Energy. The visiting groups at DESY wish to thank the DESY directorate for the hospitality extended to them.

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