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Abstract

An original method for constructing parton final states emphasizing the multi-element antenna pattern and color connectedness between partons is presented. The approach allows reconstruction of parton final states from detector registered particles while avoiding the *ad hoc* effects of a jet algorithm. This strategy connecting soft hadrons to a set of partons rather than jets is demonstrated for $q\bar{q}g$ -events and is applicable to W pair, top quark, Higgs, etc. production.

1 Introduction

A new method for reconstructing parton directions and energies is presented, enabling one to determine the color structure of a hard scattering final state. This unique approach will allow more precise and reliable reconstruction of the primary multiparton final states from the energies and momenta of the detector registered particles. This is therefore an important contribution to one of the main tasks of present and future high energy collider experiments. Since this information is so universally needed, the elimination of ambiguities, biases, *ad hoc* jet reconstruction algorithms, etc., in defining partons as jets of observed hadrons is an exceedingly valuable endeavor. These reconstructed jets enter in both precision tests of QCD and in searches for new particles and interactions. Topical examples include the search for anomalous couplings in $W^\pm$ pair production, top quark and Higgs production processes, and searches for supersymmetric particles or new gauge particles. The signatures of all these new physics phenomena typically involve the multi-jet final states as major input information.

Since the quarks and gluons are not directly observable, their fragmentation products have to be used in order to reconstruct the four-momenta of the parent partons. Traditionally, the final state structure in a hard collision process is discussed in terms of a certain number of hadron jets with specific angles, energies and masses. Various jet finding algorithms have been proposed, and they have proven to be very useful tools for analysing the experimental data. These approaches differ in many details, but all of them are based on the procedure of assigning each particle in an event to belong to a certain jet [1]. However, an attempt to force every particle in an event to belong to a certain jet is inherently ambiguous and may cause difficulties. An evident source of ambiguity is related to the interjet particles, which form a sizeable fraction of the total event multiplicity. These are distributed according to the color properties of the event as a whole and cannot be associated with any particular jet [2].

The space-energy portrait of an event contains the information on energetic parent partons, and can be characterized as a natural skeleton for registering parton kinematics. This color portrait can be used for mapping out the basic short-distance processes [3]. While the hard component of a hadron system (a few fastest particles) determines the parton skeleton of an event, the soft component (the multitude of low momentum particles resulting from parton branchings) forms the bulk of multiplicity.

In this paper, we show how to minimize the ambiguities in the reconstruction of the multi-jet final states, in particular, those caused by the collective QCD effects. The ultimate goal is to ensure that a complete picture of the

primary hard collision process is restored. We illustrate the procedure with the analysis of the generated three-jet events of e^+e^- annihilation into the $q\bar{q}g$ Mercedes-type kinematics. The event sample is processed through the full DELPHI simulation package [4].

2 From parton reconstruction to event profiles

In the following, we will describe our method of reconstructing parton combinations from their asymptotic remnants, hadrons and other secondary particles observed in a detector system. In a class of experiments, notably in the e^+e^- collisions, the whole final state can be reconstructed. It is important to note that no method can cure the fundamental problems of detection, detector inefficiencies or poor acceptance.

Our aim is to find the parton portrait of a hard scattering final state in an unbiased way, by first reconstructing the parton directions of flight (“jet axis”), and finally merging the reconstructed parton “skeletons” into a complete event by associating the particles with sets of final state partons [5]. The accuracy of our method is limited only by the detector granularity and acceptance.

The clustering algorithm is based on first fixing the hard parton directions from information given by the particles above a predetermined energy threshold. The directions are separated from each other by a minimum angle, related to the radiative properties of the original partons and the detector granularity [6]. Secondly, a search for other hard particles outside the angular cones defined by the leading hadrons is performed, with the energy threshold decreased and the required minimum angle simultaneously increased to exclude the generation of fake clusters by the fragmentation of already found clusters. To improve the clustering efficiency it is useful to introduce a requirement for finding other hard particles above some appropriate energy limit, accompanying the particles in the found directions within the given clustering cone. Finally, if a considerable proportion of the visible energy or momentum is still outside the found clusters, an extra cluster constructed around the direction of the missing momentum can be attempted.

After the particles around the found directions are combined to reconstruct the partons, the distribution of soft particles left outside the clusters can be analyzed. The probability of any unclustered particle i to be associated with a given cluster j , as a function of the particle energy E_i and the angle θ_{ij} between the directions of the particle and the direction cluster, is

defined to be

$$\omega_{ij} = \frac{C_i}{k_{ij}^2}. \quad (1)$$

The variable k_{ij} represents the squared transverse momentum $k_{ij}^2 = 2E_i^2(1 - \cos \theta_{ij})$ with respect to the direction cluster, and the sum of the coefficients $\sum_j \omega_{ij}$ is normalized to unity.

A soft particle, which is not part of a direction cluster, is assumed to be a product of an interaction between a number of final state partons. In the leading order approximation with only two partons participating in the production, each unclustered particle is assigned to the cluster pair kl for which the sum $w_{ikl} = \omega_{ik} + \omega_{il}$ is maximal. The color connection coefficient for each pair of clusters is defined as

$$W_{kl} = C \sum_i g(E_i)(\omega_{ik} + \omega_{il}), \quad (2)$$

where the index i runs through all the particles assigned to the pair of clusters, $g(E_i)$ is an energy dependent weight function [7], and the sum $\sum_{kl} W_{kl}$ is normalized to unity.

3 Reconstructing event profiles for $e^+e^- \rightarrow q\bar{q}g$ Mercedes events

For illustration of the validity of a new parton reconstruction procedure it is useful to compare with data for which all kinematic and dynamic quantities are known, event-by-event. A sample of 570.000 JETSET matrix element model [8] Monte Carlo events at the Z^0 centre-of-mass energy was selected for this analysis. In these events the directions and energies of the final state quarks and gluons were uniquely defined, and the output of the e^+e^- annihilation reaction had been processed by the complete DELPHI detector simulator [4] to match the experimental output of a corresponding experiment. The three-parton events with interparton angles $\theta_{q\bar{q}}$, θ_{qg} and $\theta_{\bar{q}g}$ between 90° and 150° ($120^\circ \pm 30^\circ$) were defined as Mercedes-like events.

The clustering algorithm was applied to the 669 events fulfilling the criteria, and the weight coefficients and color connection coefficients were calculated for the particles which were not included in the direction clusters in the 535 events left after requiring a good matching of the reconstructed directions with the original parton directions [9]. The parameters of the clustering algorithm were deduced from the detector granularity and the Monte Carlo simulation of the angular distribution of particles with respect to the directions of the final state partons.

4 Results

The distributions of the color connection coefficients between the clusters of particles representing the quark-antiquark pairs and the clusters representing the quark-gluon and antiquark-gluon pairs are presented in Fig. 1. The color connection in the quark-antiquark pair was weaker than any of the two other connections in 526 out of the 535 events, giving a gluon identification efficiency of 98% [10].

The distribution of particles not used in direction clusters is shown, together with the original parton directions and the calculated color connections, for two typical correctly clustered Mercedes-type events in Figs. 2 and 3. In order to avoid ambiguities related to the spherical coordinates, the axes are chosen as the polar angle θ and the linearly transformed azimuthal angle ϕ multiplied by $\sin \theta$. In the figures the partons are represented by the solid boxes, the size of the box being proportional to the energy of the corresponding particle. The color connections between the quark/antiquark-gluon pairs are illustrated by the solid lines, and the depletion of color connection between the quark-antiquark pairs is shown by the lack of particles along the dashed lines. Figure 2 illustrates equal color connections in both quark-gluon and antiquark-gluon pairs, with a clear depletion of color connection in the quark-antiquark pair. Figure 3 demonstrates a frequently occurring situation where one of the gluonic color connections is clearly stronger than the other, illustrated by the asymmetric experimental distribution of soft particle multiplicities. However, a clear depletion of color connection is still present in the quark-antiquark pair.

5 Discussion and Conclusions

Can the color structure of a hard scattering final state be determined on an event-by-event basis? The input into answering this question affirmatively with high efficiency is a large sample of Monte Carlo generated $e^+e^- \rightarrow q\bar{q}g$ Mercedes events for which the direction and energy of each hard and not-so-hard parton has been specified. The fragmentation hadrons are examined in the fashion we believe real detector events should be processed, according to a multi-element antenna pattern with color connections between the partons. This procedure with the few hardest hadrons specifying the parent parton direction works very well. We are in the process of making a detailed comparison of our method with the currently used main jet clustering algorithms [1]. As a preliminary conclusion, we find that our method finds the final state partons with similar efficiency compared to the typical commonly

used algorithms. One should note, however, that our method represents a new philosophy in reconstructing hard scattering final states. By using the new approach introduced here, we are currently investigating a number of e^+e^- annihilation processes, including doubly b -tagged $q\bar{q}g$ events, various QCD interference effects [11] and the $Z^0 \rightarrow ggg$ channel in three-jet events, jet-jet pairing in four-jet final states of 130 GeV and in W pair production in real data.

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Figure 1: Normalized distributions of the color connection coefficients W between the clusters representing the quark-antiquark pairs (solid line) and quark-gluon and antiquark-gluon pairs (dashed line) of the 535 correctly clustered Mercedes events.

Figure 2: Distribution of unclustered particles (empty boxes) with the directions of original partons (solid boxes) and the calculated color connections between the partons in an event with nearly equal color connections in the quark-gluon and antiquark-gluon pairs (solid lines) and clear depletion of color connection in the quark-antiquark pair (dashed line).

Figure 3: Distribution of unclustered particles (empty boxes) with the directions of original partons (solid boxes) and the calculated color connections between the partons in an event with unequal color connections in the quark-gluon and antiquark-gluon pairs (solid lines) and clear depletion of color connection in the quark-antiquark pair (dashed line).