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From jets to colour portraits of hard scattering final states

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Abstract. An original method for constructing parton final states emphasising the multi-element antenna pattern and colour connectedness between partons is presented. The approach should allow event-by-event 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 colour structure of a hard scattering final state. It is a probabilistic approach based on event-by-event analysis which retains information lost in the usual statistical analysis now in practice in jet physics. 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 endeavour. 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 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 statistical in nature based on attaching each particle in an event to a certain jet [1]. We do not do this because forcing every particle in an event to be in a jet is inherently ambiguous and sometimes 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 colour 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 characterised as a natural skeleton for registering parton kinematics. This colour 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 the multiplicity.

In this paper, we propose a method to minimise the ambiguities in the reconstruction of the multi-jet final states, in particular, those caused by the collective QCD effects[1]. 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 [5] to produce a realistic sample of events to test our procedure against.

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.

[1] Ideologically close approach based on event-by-event reconstruction was advocated in [4]

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 [6]. 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 [7]. 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 analysed. 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 normalised to unity, that therefore, defines the normalisation coefficients C_i.

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 colour 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 corresponds to all particles assigned to the pair of clusters kl, $g(E_i)$ is an energy dependent weight function [8], and the sum $\sum_{kl} W_{kl}$ is normalised to unity. C is the normalisation factor.

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 [9] 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 [5] to match the experimental output of a corresponding experiment. The three-parton events with inter-parton angles $\theta_{q\bar{q}}$, θ_{qg} and $\theta_{\bar{q}g}$ between 90° and 150° (120° ± 30°) were defined as Mercedes-like events. This acceptance range is big initially for the purpose of getting events to test our procedure with. The application of our clustering algorithm to these events was followed by the calculation of weight coefficients, (1), and colour connection coefficients, (2) for the particles which were not included in the direction clusters. The method eliminated 109 events as due to 2 jets and after making our angle cut to be 120° ± 10° 535 events were left. The clustering algorithm was applied to the 669 three-parton events with fulfilling the criteria, and the weight coefficients and colour 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. In the majority of the rejected events (109 out of 669) only two partons were reconstructed by the method. These events are typically at the limit of acceptance as Mercedes-type events. In events with correct number of reconstructed clusters the reconstructed parton directions, on the average, match with the original ones with an accuracy of 10 degrees. The angular parameters used in 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 colour 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 colour 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 jet 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 colour connections, for two typical correctly identified, clustered Mercedes-type events in Figs. 2 and 3. In order to avoid ambiguities related to spherical coordinates, the axes in these plots are chosen as the polar angle θ and the linearly transformed

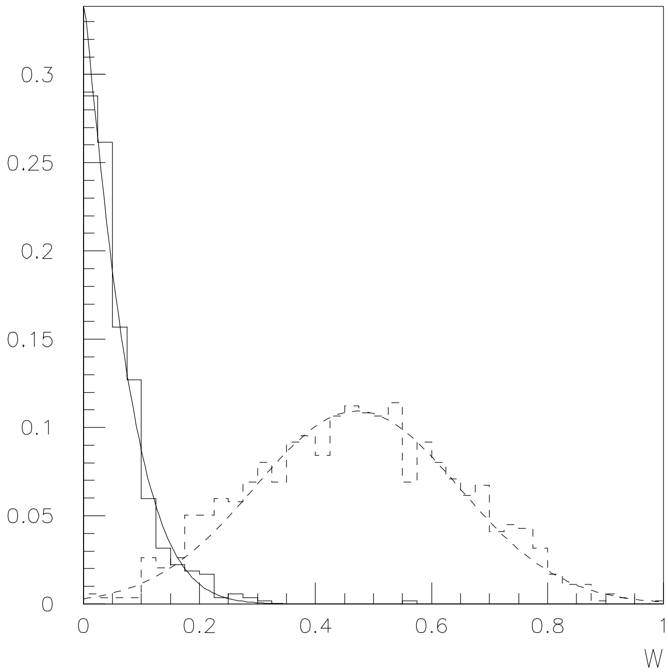

Fig. 1. Normalised distributions of the colour connection coefficients W between the clusters representing the quark-antiquark pairs (solid line) and quark-gluon and antiquark-gluon pairs (dashed line) of the 535 correctly clustered Mercedes events

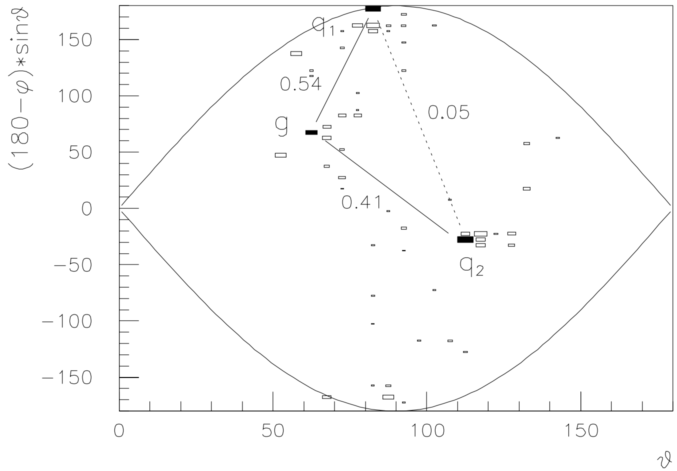

Fig. 2. Distribution of unclustered particles (empty boxes) with the directions of original partons (solid boxes) and the calculated colour connections between the partons in an event with nearly equal colour connections in the quark-gluon and antiquark-gluon pairs (solid lines) and clear depletion of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

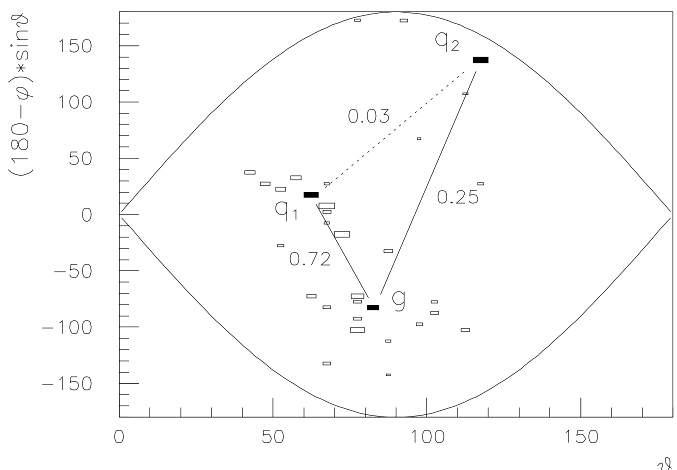

Fig. 3. Distribution of unclustered particles (empty boxes) with the directions of original partons (solid boxes) and the calculated colour connections between the partons in an event with unequal colour connections in the quark-gluon and antiquark-gluon pairs (solid lines) and clear depletion of colour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

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 colour connections between the quark/antiquark-gluon pairs are illustrated by the solid lines, and the depletion of colour connection between the quark-antiquark pairs is shown by the lack of particles along the dashed lines. Figure 2 shows an event illustrating equal colour connections in both quark-gluon and antiquark-gluon pairs, with a clear depletion of colour connection in the quark-antiquark pair. Figure 3 demonstrates a frequently occuring situation where one of the gluonic colour connections is clearly stronger than the other, illustrated by the asymmetric experimental distribution of soft particle multiplicities. However, a clear depletion of colour connection is still present in the quark-antiquark pair.

5 Discussion and conclusions

Can the colour 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 and purity is a large sample of Monte Carlo generated $e^+e^- \to q\bar{q}g$ 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 colour 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 sorts out the final state partons with similar or better efficiency and superior purity compared to the typical commonly used algorithms. One should note, however, that our method represents a new philosophy in reconstructing hard scattering final states. It is probabilistic, allowing display of the coherent antenna pattern for events and does not loose information by using a statistical approach in analysis of events. 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 $Z^0 \to ggg$ channel in three-jet events, jet-jet pairing in four-jet final states including W pair production, $e^+e^- \to H^+H^-, h^0A^0, h^0Z^0$.

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