June, 1981

DISCLAIMER

This document contains information which was developed by an agency of the United States Government. It is the property of the United States Government and is loaned to your agency. It and its contents are not to be distributed outside your agency without the express written permission of the agency to which it was loaned. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

CONF-810368--3

ON THE DETECTION AND STUDY OF NEW HEAVY PARTICLES THROUGH JET IDENTIFICATION

John B. Babcock

Carnegie-Mellon University, Pittsburgh, PA 15213

ABSTRACT

A solution to the problem of the identification of an arbitrary number of jets in high energy collisions is reviewed.¹ Some of the applications of this solution to the study of the Electroweak Interactions are illustrated through two examples: The detection and analysis of top quarks, and the detection of charged Higgs or Pseudo Goldstone bosons, in e^+e^- reactions. Although these two examples involve e^+e^- initial states, the jet identification method described in this paper could be used in the analysis of any reaction involving jets.

I. INTRODUCTION

Richard Cutkosky and I have constructed a general procedure for the identification of jets on an event by event basis.¹ By jet identification I mean the determination of the number of jets in a particular event and the matching of the hadrons, or energy fluxes in calorimeter segments, to their parent jets. Our method will identify jets regardless of their number or origin. All of our studies involve simulations of e^+e^- machines but this is solely for lack of good monte carlo simulations of other machines like e-P or PPbar machines.

The ability to identify jets² is already important at the energies attainable by the present generation of high energy accelerators,³ and ought to be of critical importance for the physics objectives of the next generation of machines. This is so because multijet events should arise from the decays of heavy objects such as heavy quarks, weak gauge bosons, Higgs bosons, or pseudo Goldstone bosons, etc., as long as the heavy objects do not decay exclusively into leptons. Fascinating multijet events should also arise from QCD interactions.⁴ One is getting a taste of this at present energies.⁵ Perhaps even the beautiful branching picture (jets within jets) that is predicted by perturbative QCD for the internal structure of jets will soon become visible.⁵

With so many potential sources, reflecting important physics, of multijet events it is important to perform as much event by event analysis as is possible in order to separate signal from noise. Of course, what is signal and what is noise depends on one's physics objectives.

Two simple examples of a general method that we are working on are the detection and analysis of top quark pair production and charged Higgs, or pseudo Goldstone, boson pair production in e^+e^- collisions. These reactions are simulated through the monte carlo programs of Ali et al..⁶ We have found that the combination of jet

Contributed Talk: Conference on Perturbative QCD at
Florida State University, March, 1981

Tallahassee

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

JBB

identification and the subsequent use of time-honored methods of traditional experimental particle physics form a powerful set of tools with which these processes can be dissected. Our results are highly encouraging and ought to be as successful when applied to the analysis of multijets arising from other sources.

This paper is essentially an introduction to our method of performing jet identification and a progress report on some of its applications. It is organized as follows: Section II consists of an explanation of the principles which underlie this jet identification. In the next 2 sections I describe the results that we have achieved so far, by applying our jet identification to the analysis of top quark and charged Higgs boson production. I have included a short description of the computer algorithm that carries out the jet identification in an appendix. Readers who are solely interested in the study of the weak interactions and how jet identification can be of use are encouraged to skip ahead to sections III and IV, and to read the rest of this paper if sufficiently intrigued.

The computer algorithms that carry out the jet identification that we use are quite small and fast (see the appendix), and are available upon request from R. E. Cutkosky or myself. These programs ought to be of use to people who are designing detectors for the new machines or already have detectors at one of the present generation of machines.

II. JET CLASSIFICATION NUMBERS AND JET IDENTIFICATION

Consider a given event with N "particles" (hadrons, photons, leptons or directed energy fluxes in a segmented calorimeter, etc.) with momenta $\vec{p}_i$, $i=1, \dots, N$. Let p_i denote the magnitude of the momentum vector $\vec{p}_i$. Now suppose that one guesses that there are J jets in this particular event and that one also has a guess as to which particles belong to which jet.

Consider the M th jet, $1 \leq M \leq J$, and define the number C_M by:

$$C_M \equiv \left[\sum_{i \in M} p_i (1 - \cos(\theta_i)) \right] / WT$$

for this M th jet. The sum in the numerator runs over all of the particles in the M th jet only and θ_i is the angle of the i th particle in jet M with respect to the M jet axis of jet number M . The jet axis is given by the direction of the total momenta of jet M which is simply the vector sum of the momentum of its constituent particles. The symbol WT in the denominator is defined by $WT = \sum_{all i} p_i$ which is approximately the total energy. We now define the "pierce" number (a measure of the solid angle pierced by jets) for this J jet hypothesis by

$$P_J \equiv \text{Min} \left(\sum_{M=1}^J C_M \right)$$

where the minimum is taken over all possible partitions of N

particles into J jets.

It is evident that a bad guess for the assignments of the particles to the jets will result in large angles θ_i of the particles with respect to the axis of their parent jet, hence large individual C_{ij} numbers, which in turn will yield a large pierce number P_J for that particular guess. Conversely an assignment that is visually sensible ought to have a small pierce number associated with it.

The pierce numbers actually perform two functions. They define the jet identification for a specified number of jets J and they characterize how successful that identification is. The array of pierce numbers for a given event forms a decreasing sequence: $P_1 > P_2 > \dots P_{N-1} > P_N$. The extremes are P_N (each particle forms its own jet) and P_1 (all particles in one jet). P_N always equals zero while P_1 equals one if the particles' momenta are measured in the center of momentum frame.

Ordinary thrust⁷ equals $1-P_2$ (2 jets) and triplicity⁸ equals $1-P_3$ (3 jets), hence our scheme is a generalization of those concepts to the identification of an arbitrary number of jets. I should like to point out that our measures are perturbatively stable and well defined, as thrust and triplicity are. As a by-product of perturbative stability, these measures are also stable under resonance decays and cascades occurring within jets from the strong and electroweak interactions. This stability is particularly relevant to current applications for these reasons and because such measures are also stable against detection inefficiencies like those arising from finite size calorimeter segments.

How can one use the pierce numbers to decide on the number of jets? We were previously fixing the number of jets J and finding the best assignment of the N particles to the J jets. Now we want to look at the array of different pierce numbers P_J , varying J , and make a decision on the number of jets in a particular event. Simply choosing that J which gives the smallest P_J is clearly ridiculous as that is given by $J=N$, i.e. each particle forms its own jet. It seems to me that there are two facets to this problem. In perturbative QCD, without hadrons, the number of jets in an event is purely a convention because the branching never stops.⁵ In this non-hadronic world one could simply define the number of jets by cutting on the pierce numbers: $P_1 > \dots P_{J-1} > P_{\text{cut}} > P_J > \dots P_N$, where P_{cut} is arbitrary. That is, if $P_{J-1} > P_{\text{cut}}$ and $P_{\text{cut}} > P_J$, then the number of jets in this particular event is defined to be J . This is a simple generalization of the procedure of cutting on thrust to separate 2 jet events from 3 jet events. Recall that a thrust cut is the simplest cut that will separate 2 from 3 jet events.

Just as the formation of hadrons puts an end to the perturbative branching,⁹ it also puts limits as to which pierce cuts are sensible. This is the other aspect of this number of jets question. It would seem that such sensible cuts ought to be determined by trial and error as they will depend upon the machine, detector, physics objectives, available energy and perhaps a desire to force certain higher order corrections to be small.

We have defined some other numbers which are derived from the

pierce numbers in order to facilitate this investigation of sensible cuts. They are:

$$\text{Thrust #'s: } T_J \equiv (P_{J-1} - P_J)$$

$$\text{Zap #'s: } Z_J \equiv (J-1)(T_J - T_{J+1})$$

$$\text{Grove #'s: } G_J \equiv 1 - \sum_{M=2}^J Z_M$$

As a simple illustration we consider the separation of 2, 3 and 4 Feynman-Field¹⁰ jets at 30 Gev in optimal configurations. That is, the 2 jets are back to back with 15 Gev of energy each, the 3 jets are in Mercedes Benz configuration with 10 Gev of energy each, and the 4 jets are in a tetrahedral configuration each with 7.5 Gev of energy. This was done a year ago and at the time we were studying the jet numbers as a function of overall multiplicity which was chosen to be 18 in this case. The average values for the pierce,

thrust, zap and grope numbers are shown in Fig. 1.

It is clear from the pierce graph, for example, that a $P_{\text{cut}} = .12$ would be sufficient to cleanly separate the different types of jet topologies from each other. It is also rather clear that one does not gain very much, in terms of a decrease in the pierce numbers, when the jets themselves are being chopped to pieces. For example, the change in pierce numbers from the 3 jet assignment to the 4 jet assignment for the 4 jets in a tetrahedral configuration is about a factor of 3 to 4, while the change in pierce numbers in going from the 4 jet assignment to the 5 jet assignment is about a factor of .3. Amusingly, the zap numbers tend to peak (or zap) at the correct jet assignment while the grope numbers seem to fall off of a cliff. Of course most 4 jet events do not lie in a

Fig. 1. Jet identification #'s vs. jet hypothesis (J) for 2 jets (circles), 3 jets (triangles) (in a M.B. config), and 4 jets (squares) in a tetrahedron at 30 Gev.

tetrahedron and hence P_2 and P_3 will be smaller for a typical 4 jet event, i.e., they will look more 3 jet-like.

Users of our system may wish to toy around with cuts on

external angles between jets versus the internal angles of the jets and/or jet invariant masses, etc. These things are all very easy once the jets have been identified. For example, we are looking at ratios of zap to grope numbers to help separate signal from noise for charged Higgs pair production in e^+e^- annihilations. It is possible that one may want to discard soft particles and/or combine nearby neighbors prior to running the jet identification routines which will then simply run faster.

I should like to mention the following useful feature of the "groping" routines that carry out this jet identification. Namely the method returns, automatically, all possible jet assignments, starting with the number of jets equal to the multiplicity down to the 2 jet assignment. This information is useful for deciding on how many jets there are in a given event. The computer programs themselves do not make the decision on the number of jets; this is made by the user who then fetches the particle assignments out of the appropriate common blocks. Once the event has been groped it does not have to be regroped as once is quite sufficient.

So the number of jets has been decided upon and identified. What does one do now? The answer is to go after the interesting physics by combining this identification with some of the impressive tricks that experimental particle physicists have developed over the past 30 years. Two examples of this sort of combination of techniques are given in the next two sections.

III. TOP QUARK IDENTIFICATION AND ANALYSIS

We consider the analysis of top¹¹ quark pair production in e^+e^- machines with total energy in the center of mass ranging from 40 Gev to 100 Gev (the 20 mass rounded off to the nearest 100 Gev), and top quark masses between 20 Gev and 50 Gev. The monte carlo programs of Ali et al.⁶ are used to simulate these events which we then attempt to pick apart (as one would analyze a bubble chamber photograph) using our jet identification or groping routines. The simulation consists of a series of cascades involving Feynman-Field quark fragmentation followed by weak (parton like) decays of top and bottom mesons. The cascades are generated in the appropriate "time" sequence with tops decaying into bottoms + ordinary hadrons + (sometimes) leptons, followed by bottoms decaying into charm + ordinary hadrons + (sometimes) leptons and so forth. So a bottom quark jet is a rather complicated fat jet, a charm quark jet is less complicated while up, down and strange quark jets are simple Feynman-Field jets.

The heavy fragmentation functions which parametrize the momentum fraction of a heavy quark jet that is carried by the appropriate heavy meson were chosen by us (the original code had different heavy fragmentation functions) to be:

$$f_{H/h}(z) \sim 1/((1-z)^2 + (1/M_H)^2)$$

a form that is similar to those suggested by Suzuki¹² and Bjorken.¹³

Because of this choice the bulk of the energy is carried by particles which are decay products of the top mesons rather than being carried by the light hadrons which were formed during the initial fragmentation of the top quarks. Of course, this choice for the heavy fragmentation functions makes the problem of jet identification simpler. We are working on procedures which can be followed if this choice turns out to be substantially incorrect. But for now we ignore the problem. Light hadrons from the initial fragmentation are simply misidentified as belonging to the decay products of the top mesons, a procedure which is adequate as long as these initial hadrons do not carry significant fractions of the total energy.

A typical $T\bar{T}$ event will then give rise to one of the following 3 jet topologies:

I) 2 jets + 2 leptons + 2 neutrinos. This occurs when both top mesons decay semi-leptonically.

II) 4 jets + 1 lepton + 1 neutrino. This occurs when one of the top mesons decays semi-leptonically while the other decays non-leptonically.

III) 6 jets. This occurs when both top mesons decay non-leptonically.

Events of type I are the simplest visually, but the kinematics cannot be determined because there are 2 prompt neutrinos. Events of type III are the most complicated. We therefore focus on events of type II (see Fig. 2).

We now attempt to isolate a clean sample of events of type II by applying a series of cuts which can be carried out in the lab. I list below the first 3 cuts which we found to be helpful.

1) An event is discarded if there are no fast muons or electrons. Fast leptons are supposedly prompt leptons coming from the decays of the top meson. This cut ought to eliminate most events of type III). 2) An event is discarded if there are two or more fast muons or electrons. This could happen if a fast lepton came from the decay of a bottom or if the event were of type I). 3) An event is rejected if the missing energy is not approximately equal to the magnitude of the missing momenta. In the simulation this is caused by the occurrence of two or more fast neutrinos while in the lab it could also be caused by acceptance problems.

At this point the jet identification algorithms are used, i.e., the event is groped (the 2 prompt leptons are set aside; they are not fed to the groping routines). If the pierce numbers P_2 and P_3 are too small, then the event is rejected. This is cut number 4). We then pull out the 4 jet assignment and attempt to guess which jet belongs with the prompt lepton and neutrino (the semi-leptonic bottom), the other 3 jets being fragments of the top meson which decayed non-leptonically. We simply try all 4 combinations with the correct one being given when the invariant mass of the combination of one of the jets + the prompt lepton + the prompt neutrino most equals the invariant mass of the combination of the other 3 jets. If the invariant masses of the correct combinations are not sufficiently close to the top mass then we discard the event. This is cut number 5). We are assuming here that the top mass is

already known, e.g., toponium has been found. If this is not the case, then this cut can be skipped, and one can accumulate histograms of the invariant masses of these triples of partons, and look for a bump. An example of this sort of bump hunting is given in the next section on charged Higgs pair production.

Incidentally, looking at the 4 jet assignment costs no extra computer time as this is simply one of the many jet assignments which were worked out in the process of calculating the pierce numbers. It is simply a matter of pulling the appropriate information out of a common block.

Finally, we reject events in which one of the individual jet masses is too small. This has very little effect on the number accepted but does tidy up some of the Dalitz plots at the edges. This is cut number 6).

The effects of these cuts at 100 Gev with 50 Gev top mesons are shown in Fig. 3. Of 20000 generated tops, 6% survived the cuts, most of the others being rejected because they were not of type II), while 0 out of 20000 generated bottom quark events survived the cuts. This is one example of the sort of massaging that is possible with jet identification in order to enhance the signal above the noise.

We now have a fairly pure sample of $T\bar{T}$ events in which

Fig.2. An illustration of events of type II (see Sec.III). Note: b jets hadronize via a series of cascades while u jets (e.g.) are Feynman-Field jets. There are initial light hadrons associated with the t quarks which are not shown. The decays of the t quarks take place inside of top mesons.

Fig.3. Effects of cuts at 100 Gev $e^+e^- \rightarrow t\bar{t}$ (50 Gev)

one of them decayed semi-leptonically while the other decayed non-leptonically. We have also decided, event by event, which hadrons belong to which jets (jet identification) and which jet is the semileptonic bottom jet.

The next step is to analyze the semi-leptonic side. To this end we go to the rest frame of the semileptonic bottom jet + prompt lepton + prompt neutrino, and calculate the bottom jet energy and prompt lepton energy in this frame. This event then contributes a point in a Dalitz plot with bottom energy and prompt lepton energy as y and x axis respectively. An example of this sort of Dalitz plot is shown in Fig. 4. Two histograms are extracted from each Dalitz plot. One histogram is given by summing all of the numbers in a given column which yields the prompt lepton energy spectrum. The other histogram is calculated by summing the top 5 numbers in a given column. This was done to get rid of boundary effects, and thus reflects the behavior of the square of the matrix element more directly. The two histograms are plotted on top of each other with the latter being denoted by stripes. Some of the results are shown in Figs. 5 through 7. As a diagnostic device, the results of performing the above analysis when the jet identification is artificially known (only possible in a monte carlo) are compared with the groping results (possible in the real world).

Fig.4. Dalitz plot of semi-leptonic side $E=40$ Gev, $M_T=20$ Gev. Summing the #'s from the top to the dotted line, for a given column yields the striped histograms of Fig.5-7.

Fig.5. $E=100$ Gev $M_T=50$ Gev

Fig. 6. $E=100$ GeV $M_T=20$ GeV

Fig. 7. $E=40$ GeV $M_T=20$ GeV

The results obtained by cheating versus not cheating are virtually indistinguishable for the highest energies and top masses, while for the other choices of energies and top masses the results bear a strong similarity to each other. The analysis is clearly able to distinguish between a phase space (P.S.) distribution for the three partons (bottom, lepton and neutrino) and the distribution given by the square of the V-A matrix element, especially if one looks at the high energy end of the striped distribution. The biases introduced by the lepton energy cut are evident and rather simple to understand.

Now, what about the non-leptonic side, that is, the other 3 jets? Are they worth analyzing? It would seem that the analysis

of these 3 jets is considerably more difficult than the analysis of the semileptonic bottom jet + the two prompt leptons, primarily because we don't know which of the three non-leptonic jets is the non-leptonic bottom jet, the up (or charm) quark jet, and the down (or strange) quark jet, respectively. One can still use folded Dalitz plots, etc., as tools and the extent to which these studies work will be shown in a forthcoming paper.

It is possible, however, that the non-leptonic decays of the top quark are mediated by a charged or neutral flavor changing Higgs bosons (or pseudo-Goldstone boson) with a mass less than that of the top quark¹⁴ (see Fig. 8). It would then seem obvious, given that the jets can be identified, that one ought to look at the invariant masses of all possible pairs of the three non-leptonic jets in order to investigate this possibility. An example of this sort of analysis is shown in Fig. 9. It is clear from these histograms that while it is tough to tell V-A from phase space (the folded Dalitz plots are more sensitive for this purpose), it is quite easy to deduce whether or not a Higgs or Higgsomime¹⁵ is mediating the decays of the top quark. It is also possible to deduce the mass of said Higgs boson in this manner as is evident from Fig. 9.

An astute reader will have noticed, however, that if such a boson exists, most of the $T\bar{T}$ events will be of type III where both tops decay non-leptonically yielding 6 jet events. We have not performed this analysis yet, but it should proceed in a way that is similar to the analysis of events of type II.

Fig.8. An illustration of events of type II (see Sec. III and Fig.2) if a real Higgs or pseudo Goldstone boson mediates the decay of one of the tops.

IV. CHARGED HIGGS OR PSEUDO-GOLDSTONE BOSON PAIR PRODUCTION AND IDENTIFICATION IN e^+e^-

If charged Higgs or pseudo-Goldstone bosons exist, then they ought to be copiously produced by pair production in e^+e^- collisions (1/4 of a step in R asymptotically) if one has enough energy.¹⁶ These would not be rare processes and ought to be easily detected.

Fig.9. Histograms of the squares of the invariant masses of all pairs of the 3 non-leptonic jets. $E=100$ Gev, $M_T=50$ Gev, $M_H=30$ Gev

jet assignment is pulled out of the appropriate common blocks and the invariant masses of all possible pairs of jets are calculated. A sample histogram of this quantity is shown in Fig. 11, where a clear Higgs peak (at the correct mass) is visible sitting on top of a combinatorial background. One can also select which pairs of jets belong together, by virtue of having come from the same Higgs, by simply pairing them together and selecting that combination which yields the most equal invariant mass for the two pairs. This device is designed to suppress the combinatorial background. A histogram of the mass of this correct pair combination is shown in Fig. 11.

We shall see that this is indeed the case if one uses jet identification.

We simulate these events by first generating the kinematics for the Higgs pairs. Each Higgs boson then decays into bottom and charm quark respectively which are presumed to be the heaviest fermions available. These decays are generated in the individual Higgs rest frames. The bottom and charm quarks are now turned into jets of hadrons, leptons and photons by the monte carlo programs of Ali et al.⁶ This then constitutes the simulation of these events (see Fig. 10).

The events are then groped, that is, the jets are identified. The four

Fig.10. Illustration of charged Higgs or pseudo-Goldstone boson pair production yielding a 4 jet event.

Fig.11. Invariant mass histograms for charged Higgs (or P.G.B.) pair production (see Fig. 10).

$E=100$ GeV $M_H=30$ GeV

The average value of the mass of the Higgs is within 1% of the correct (input) value in this case while the dispersion is caused by particle misidentification and missing neutrinos since the Higgs was generated with zero width.

At the present time we are studying this problem with a wide range of energies and Higgs masses (we are going inside of the DESY range). We are also studying the problem of backgrounds from QCD (how to eliminate them) and the problem of kinematical reflections near threshold. This should be available shortly in a paper on Higgs pair production by R. E. Cutkosky

and myself. It is amusing to ponder the possibility that such bosons may be heavy enough to decay to top and bottom quarks, in which case one will need the ability to identify top quarks (see Sec. III).

It would seem that the detection of Higgs or pseudo-Goldstone bosons is inextricably tied up with jet identification if they are heavy (greater than 15 GeV say) because they are expected to decay into the heaviest fermions available. Higgs bosons that do not couple in this manner will simply be easier to detect by jet and/or lepton identification.

In a few cases it may be possible to avoid jet identification and discover Higgs bosons by looking at recoil energy spectra.^{17,18} But I believe that the use of jet identification may well augment these devices by providing some extra cuts, which may prove important, especially if the recoil energy is not precisely measured. The question of signal versus noise is more important for the detection of the Higgs boson of the Weinberg-Salam¹⁹ model than for the heavy particles discussed in this paper because the production of this neutral boson is expected to be genuinely rare. At any rate, one would surely be curious about the nature of the beast that is on the other side of the event from the recoiling photon or di-muon pair.

SUMMARY

A useful way to think of jet identification is that it is simply a necessary step between hadron identification and the identification of the quanta which appear in the fundamental Lagrangians of

particle physics, such as the QCD²⁰ and electroweak¹⁹ lagrangians. After the jets have been identified, the powerful methods and intuition of traditional experimental particle physics can be used. The use of jet identification allows one to separate signal from noise and to analyze that purified signal in reactions involving jets.

It is instructive and enjoyable to glance over some of the many excellent papers and review articles which deal with the phenomenology of the next generation of high energy machines with jet identification in mind.¹¹ It rapidly becomes clear by doing this that challenging jet identification problems ought to be abundant for the next decade (perhaps longer?) of experimental physics.

The reader is simply invited to consider the detection of one of his or her favorite exotica, like top quarks, weak gauge bosons, Higgs bosons, pseudo-Goldstone bosons, new heavy leptons etc., and follow the decay of said beast, perhaps through multiple cascades, to the point where light quanta like bottom quarks, gluons and leptons emerge. Those final quanta which are energetic and have ordinary color will turn into jets. At this point one is commonly faced with a problem involving jet identification.

In a serious effort to discover or eliminate such a beast it is crucial to be able to separate events which are reasonable candidates for this favorite particle from the rest of the ordinary and more numerous (perhaps much more numerous) events. If a reasonable signature is not found, then I do not believe that the interesting particle (or physics) itself will be found, at least not to other people's satisfaction, as one will probably be reduced to squinting at various unconvincing histograms which can be argued about forever.

On the other hand, if a reasonably purified sample of one's favorite particle can be obtained, then it can be examined further in order to estimate masses, branching fractions and so forth. Jet identification has an important role to play both in defining the signature and in the subsequent analysis.

I would like to thank the organizers of this conference for providing a very pleasant and exciting atmosphere for fruitful intellectual exchanges.

I would also like to thank my colleagues at Carnegie-Mellon University for their encouragement and wisdom, and at Rutherford Laboratory where much of the early setup work on this project was performed. Most of all I would like to thank my collaborator Richard Cutkosky. This research has been supported in part by the U.S. Department of Energy.

APPENDIX: JET IDENTIFICATION ALGORITHM (GROPE)

In Section II I described the minimum principle which underlies our solution to the problem of jet identification. The purpose of this appendix is to outline the computer algorithm which carries out this identification. This is a question of tactics. The algorithm is iterative with the solution for the J+1 jet assignment forming the input for the J jet assignment. The starting point for

the iteration is the $J=N$ (N =multiplicity) assignment for which the identities of the jets are obvious as each particle forms its own jet.

We now suppose that at some intermediate state we have an optimal, or near optimal, assignment of the particles to $J+1$ jets. That is, the assignments are such that P_{J+1} is close to the absolute minimum for $J+1$ jets for this particular event. The J jet assignment is then constructed through the following steps which consist of one iterative cycle:

a) Combine that pair of jets which leads to the minimum increase in the pierce number, that is, for which $(P_J - P_{J+1})$ is the smallest number. One has to pay some price for decreasing the number of jets, but one wants to pay the smallest price. For example, suppose that one is contemplating combining jet numbers I and K to form a new jet which we shall call L (see Fig. 12). Then the increase in pierce number is given by:

$$1) P_J - P_{J+1} = \Delta C = C_L - C_I - C_K$$

$$[|\vec{P}_I| + |\vec{P}_K| - |\vec{P}_I + \vec{P}_K|]/WT$$

where $\vec{P}_I \equiv \sum_{i \in I} \vec{p}_i$, $\vec{P}_K \equiv \sum_{i \in K} \vec{p}_i$, which are the vector momenta of jets I and K respectively.

Fig. 12. One iterative (groping) step consisting of substeps A & B.

It is clear from this expression that small increases in pierce number are given by combining jets which are roughly collinear, or jets for which one or both of the jets are soft. One then simply checks all pairs of jets $1 \leq I \leq K \leq J+1$ and chooses the pair for which expression 1) yields the smallest number. The chosen pair (I,K) are now combined into a new jet L and hence we now have J jets instead of $J+1$. Please note that when I speak of combining jets or transferring particles, I mean putting tags or labels upon them; physical momenta are never altered. We now have an assignment of particles to J jets and an associated pierce number

P_J .

b) In this second step the program checks to see if one can obtain a smaller P_J number by single particle transfers between the

new jet L and the other older jets in the event; if so, the transfer is carried out. If an old jet has a particle or particles transferred into or out of it, it becomes an altered jet. Altered jets are then treated as new jets which are paired against all other jets to check for improvements in P_J which can be brought about by single particle transfers. This step terminates when no such improvements are to be found.

This is a complete cycle of the iteration which is then repeated to build up the J-1 jet assignment, and so forth. The approximation consists of not considering simultaneous transfers of many particles amongst many jets to obtain a smaller pierce number P_J . One can imagine a tower of approximations being built upon this one. We have, however, included a provision for checking transfers of 2 particles at a time; we had in mind resonance decays, which yield decreases in the pierce numbers which are much less than 1%.

A scattergram of the computer time that is necessary to carry out all iterations, that is, all of the near best assignments to all possible numbers of jets, is shown in Fig. 13. One can see from this figure that the computer time is quite reasonable, and does not constitute a hindrance in the use of this system.

It is important to emphasize that the groping routines do not decide on the number of jets in a particular event. The user must assume this responsibility. To be brutally explicit, the groping routines are used in the following way:

- 1) The user first loads the multiplicity and the vector momenta of the individual particles into a common called /HADRON/. Of course, a tremendous amount of analysis must precede this step in a real experiment, which one could think of as particle identification. Please note that particle could mean hadrons, leptons, photons, directed energy flows in calorimeter segments, etc., or combinations of these things (detectors are rarely completely uniform). The momenta might be well known for some particles and merely guessed for others. Two examples of such guesses, to partially compensate for missing information, are given in the appendix of Ref. 1.

- 2) The user now executes the command CALL GROPE which carries out the jet identification described in this appendix in a few

Fig.13. CPU time for all possible jet hypotheses from the # of jet = multiplicity to the 2 jet assignment.

seconds of CPU time (on a VAX).

3) The user must now decide on the number of jets. The user could do this by cutting on the pierce or other numbers which are to be found in the /JETS/ common. The user might prefer to cut on other things like angles between jets, jet-jet invariant masses etc. which can be trivially calculated from the jet kinematics which can be found in the /JETSAV/ common. One example of the use of a combination of cuts is given in section III of this paper. A useful set of cuts could be guessed at by performing monte-carlo studies, for example, and such cuts would clearly depend upon the energy of the beams, type of machine, physics objectives, limitations of the detectors (perhaps) etc. Of course, we could have installed a canonical set of cuts and the number of jets would have just popped out but this would have drastically diminished the systems' flexibility.

4) Having decided upon the number of jets, the user can now fetch the jet kinematics and the tags that label which particles belong to which jets. These things are to be found in the /JETSAV/ common. Armed with this information, the user might calculate the number of kaons in a particular jet (perhaps a clue to its flavor), the mean transverse momenta or rapidity of particular jets, the contribution of this event to various Dalitz plots or energy distributions, etc. - whatever is relevant for an understanding of the underlying physics.

And on to the next event.....

REFERENCES

1. J.B. Babcock and R.E. Cutkosky, Nucl. Phys. B176, 115 (1980).
2. Other papers dealing with the jet identification problem include:
K. Lanius, DESY 80/36
H. J. Daum, H. Meyer and J. Burger, DESY 80/101
J. Dorfman, SLAC-PUB-2625
S. L. Wu, DESY 80/127.
3. See, for example, the talk of H. Meyer in this conference.
4. For example: J. Ellis, M. K. Gaillard and G. Ross, Nucl. Phys. B111, 255 (1976);
T. A. DeGrand, Y. J. Ng and S. H. Tye, Phys. Rev. D 16, 3251 (1977);
A. Ali et al., Phys.Lett. 82B, 285 (1979); Nucl.Phys.B167, 454, (1980);
R. K. Ellis, D. A. Ross and A. E. Terrano, CALT 68-785;
also, the talks given by D. Ross and G. Schierholz in this conference.
5. For nice reviews see:
K. Konishi, RL 80-099 and his talk at this conference.
S. Wolfram, CALT-68-778.
6. We are deeply grateful to Esko Pietarinen for promptly sending us a tape of the monte carlo programs developed by him and his co-workers. I believe that the references include:
A. Ali, E. Pietarinen, G. Kramer and J. Willrodt, Phys. Lett. 93B, 155 (1980).

- A. Ali, J. G. Korner, G. Kramer and J. Willrodt, Nucl. Phys. B168, 409 (1980).
7. S. Brandt et al., Phys. Lett. 12, 57 (1964);
E. Fahri, Phys. Rev. Letters 39, 1587 (1977).
 8. S. Brandt and H. D. Dahmen, Z. Phys. C1, 61 (1979).
 9. See, for example, the talk of R. Field in this conference.
 10. R. D. Field and R. P. Feynman, Nucl. Phys. B136, 1 (1978).
 11. A nice review of the phenomenology of heavy particles is contained in the article by J.D. Bjorken, Fermilab-Conf-80/86-Thy.
 12. M. Suzuki, Phys. Lett. 71B, 139 (1977).
 13. J. D. Bjorken, Phys. Rev. D 17, 171 (1977).
 14. This possibility is mentioned in: "The Phenomenology of Higgs Particles in Gauge Theories" by Bruce McWilliams which contains a very nice summary of Higgs Phenomenology. Thesis, Carnegie-Mellon Univ., 1980.
 15. S. Dimopoulos, Nucl. Phys. B168, 69 (1980).
 16. J. F. Donoghue and L. F. Li, Phys. Rev. D 19, 945 (1978);
H. E. Haber, G. L. Kane, and T. Sterling, Nucl. Phys. B161, 493 (1979).
For Pseudo-Goldstone bosons, see:
E. Fahri and L. Susskind, Ref-Th. 2975 and references contained therein.
 17. J. D. Bjorken, Proceedings of the 1976 SLAC Summer Institute.
 18. F. Wilczek, Phys. Rev. Letters 39, 1304 (1977).
 19. S. Weinberg, Phys. Rev. Letters 19, 1264 (1967).
A. Salam in "Elementary Particle Theory", ed. N. Svartholm, (Almqvist and Wiksell, Stockholm 1968), p.367.
 20. D. J. Gross and F. A. Wilczek, Phys. Rev. Letters 30, 1343 (1973);
H. D. Politzer, Phys. Rev. Letters 30, 1346 (1973).
 21. For example: Refs. 11, 14, 15, 16 the LEPP summer studies...