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SUMMARY REPORT OF THE JET-STUDY GROUP

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Summary

Predictions for jet physics at SSC energies are reviewed. Comparison is made with data at CERN collider energies. The work of the Jet Study group had much overlap with the work of the Detector Groups and the Fragmentation Group.

Introduction

It is now well established that the partons of quantum chromodynamics (QCD) manifest themselves as jets when probed at large values of momentum-transfer squared (q^2).[1-2] Events like those of Figure 1 are copiously produced at the CERN SPS-Collider. The measured jet rates and angular distributions are in good agreement with QCD predictions.[3] There is no doubt that events with high E_T will have a jet-like structure at the SSC. By the time the SSC is in operation, even more stringent tests of QCD will already have been made at CERN and Fermilab. The main motivation for predicting jet-properties at the SSC is that QCD jets will be the dominant background for "new physics".

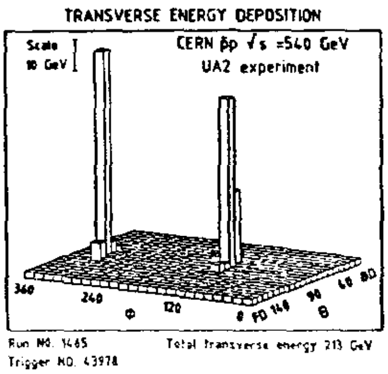

Fig. 1
Transverse energy deposition, polar angle vs. azimuth, for a hard-scattering event observed in the UA2 experiment at the CERN SPS-Collider (270 GeV x 270 GeV proton-antiproton collisions).

The definition of a "jet" is somewhat vague. For a theorist it tends to mean the fragmentation products of a single parton,whereas for an experimentalist it is the result of some clustering algorithm applied to the hadrons in the final state. Experimentalists' jets are easy to find. At the CERN SPS-Collider there is a large cross section, approximately a thousand times the single particle cross section, for energy flow into a small solid angle, typically a few per cent of 4π steradians. The separation of these jets from the background, which is approximately flat in rapidity, becomes more distinct with increasing jet transverse momentum,because the physical size of the jet remains roughly constant. The most difficult problem is the association of these observed jets with specific parton sub-processes, in order to make contact with theory.

At the SSC the basic hadronic unit will be the jet. Experiments will be designed to measure the four-vectors of jets, analogous to measuring the four-vectors of pions at lower energies. The rate of 1 TeV jets per 100 GeV energy bin is predicted to be about 1 per second at an SSC luminosity (20 TeV x 20 TeV proton-proton collisions) of 10^{33} cm^{-2}sec^{-1}.[4] It is essential to know what these jets will look like in order to design experiments to search for new physics which may be observable above this QCD background.

This report is organized into two main parts: a section devoted to the more experimental questions and a section on the open theoretical issues.

Properties of Hard-Scattering Events

What do jets look like in SSC events? Two large Monte Carlo programs were used at Snowmass to generate SSC (20 TeV x 20 TeV proton-proton collisions) hard-scattering events, "Isajet"[5] and "Fieldajet".[6] These are amongst the most sophisticated Monte Carlo programs available today for modelling high energy pp collisions. However both of them have shortcomings even at CERN collider energies. It was therefore felt that the results of these Monte Carlo programs were only indicative, and that it was important to isolate the sources of any differences between them. Both programs begin with 2 → 2 processes calculated from QCD, but then differ in the details of the methods used to describe the development of the parton shower. In addition, Isajet does not have initial state bremsstrahlung while Fieldajet does. Qualitatively, Fieldajet predicts more complicated event topologies than Isajet. The Fieldajet events have a larger number of soft jets than Isajet. A detailed comparison of some results of the two programs is given in a report by Huston.[7]

We may use the energy profile (energy per unit of rapidity) of jets measured at the CERN collider as a benchmark to check the Monte Carlo results.

In Figure 2 we show the energy profile (data from the UA1 experiment at CERN) of the superposition of many jets about a common axis for various jet transverse momenta. We emphasize that this is an average distribution; however, about 85 % of the events have only two jets with $E_T > 15$ GeV. (Of course, this fraction is sensitive to the E_T threshold above which one counts jets.)

The two-jet events dominate the prominent spikes of Figure 2. The other 15 % of the events have more complicated topologies and are responsible for the shape of the tails. The energy flow plots from CERN have the following features: a) a central sharp jet core which grows with increasing jet p_T, b) a non-gaussian region near the jet core, and c) a constant flat background level. If there is a contribution to this background level due to processes involving multiple low-x gluons, then this background plateau could be much higher at the SSC because the same copious low-x gluons will then have much higher energy.[8]

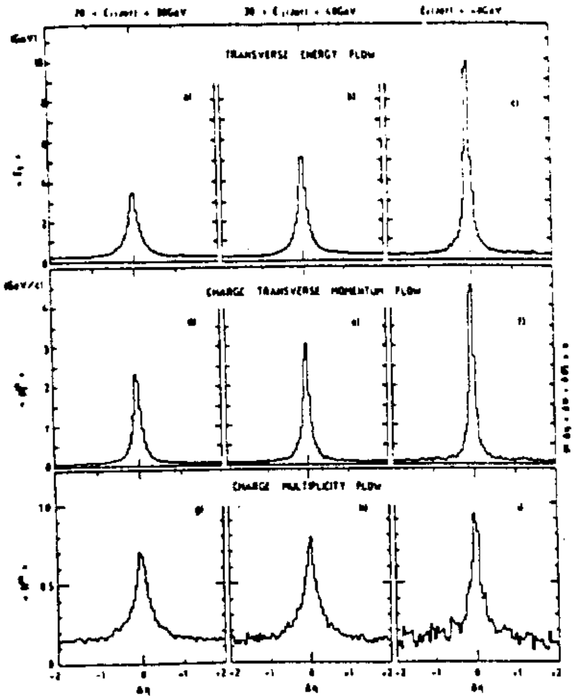

Fig. 2

(a-c): Transverse energy flow as function of $\Delta\eta$, i.e. pseudorapidity distance from the jet axis[6] for 3 slices of jet E_T. Cells inside $\Delta\phi = \pm 90^{\circ}$ are used.

(d-e): Charged transverse momentum flow as function of $\Delta\eta$.

(g-i): Charged multiplicity flow as function of $\Delta\eta$.

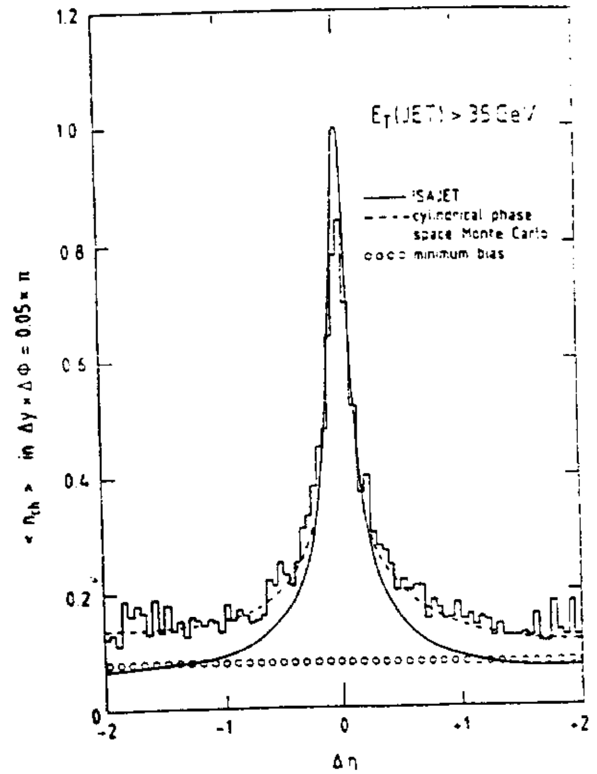

Fig. 3

CERN data (270 GeV x 270 GeV proton-antiproton collisions) on the charged particle profile as a function of distance from the jet axis together with the predictions of Isajet. The level of minimum bias events is also indicated.

Figure 3 shows an enlarged view of the charged particle multiplicity for CERN SPS-collider jets with $E_T > 35$ GeV. The prediction of Isajet (no adjustments!) is shown (solid curve). We see that Isajet is about a factor of two too low in the wings at distances of about 1 unit of pseudorapidity from the jet axis. Fieldajet (not shown here) is about a factor of two too high in the wings. Isajet is too clean and Fieldajet is too dirty; the true answer, at least at CERN energies, is somewhere in-between.[9]

Measurement of multi-jet masses will be of particular interest at the SSC. Jets will be trivial to identify at the SSC and energetic jets will be easily measured with good resolution. In this sense di-jet masses will be measured to a couple of percent in the TeV mass region. However, there will still be the problem of identifying a jet with an individual parton because, for example, the partons do not fragment independently. Except for one recent example of low statistics,[10] jets have not been sucessfully combined to form the mass of a decaying particle. There will be some mass resolution limit imposed by the statistics of the fragmentation process which is expected to be at the level of a few percent.

Precise measurements of individual jet masses are of limited usefulness.[11] This is because the mass of a jet is dominated by the fragmentation process which is statistical in nature. In fact, because partons cannot fragment independently (and conserve energy and momentum) the concept of a single jet mass has little physical meaning. A clear example of this is the case of PEP or PETRA jets where the five different quark flavors of varying masses may not be distinguished by their jet masses. For CERN-collider jets, a typical jet mass is about 25 GeV with large fluctuations (10's of GeV) from jet-to-jet. Jets at the SSC will have even larger masses.

Heavy flavors in jets is the subject of an entire other working group.[12] We remark here that charm and bottom quarks are expected to be copiously produced in SSC jets. Top-quarks are expected to be present at the percent level in very high E_T events.

Finally, we make a few general remarks about detectors which might be appropriate for jet measurements.[13-14] It is clear from existing measurements that although high E_T jets have a dense core, the tails can spread out to about 60 degrees from the jet axis. Therefore one needs large solid angle coverage to make jet measurements. Jets are composed mostly of gammas from π^0 decays and charged pions. Since there are large fluctuations of the neutral and charged pion jet energy fractions from event to event, one desires an energy measurement having a uniform response for gammas and hadrons. One practical proposal is to construct the calorimeter out of uranium.[15] Transverse cell segmentation should be about the same size as the hadronic shower size (roughly an absorption length).[16] The calorimeter should be thick enough to fully contain jets with energies of several TeV which will require about 15 absorption lengths.

Theoretical Issues

Several theoretical issues were raised at Snowmass, but few of them were fully resolved during the course of the workshop. The most important is the question of how to formulate the theory in order to make a close connection with the jets observed experimentally. Experimental data are analysed by performing a series of cuts to exclude particles not associated with the jets. These cuts define what is meant by a jet both experimentally and theoretically and hence in the comparison with theory one is naturally led to a Monte Carlo approach. Most Monte Carlo models contain a parameter Q_0, the jet mass which delineates the border between perturbative QCD physics and the phenomenological model of fragmentation into colour singlet hadrons. Eventually we may hope to understand the confinement mechanism well enough to fully describe the hadronisation from first principles; in such an approach the parameter Q_0 would no longer be present. A more modest aim for present purposes is to include as much as possible of correct perturbative QCD physics above the scale Q_0.

Two main features were felt to be lacking from the perturbative sector of many Monte Carlo programs,(and in particular from Isajet and Fieldajet).

(a) the corrrect treatment of soft QCD radiation.

(b) the inclusion of the $2\to3$ and $2\to4$ parton subprocesses.

The old description of jet development is based on the observation that leading collinear singularities are correctly given by the summation of tree diagrams in a physical gauge neglecting interference. Recent theoretical work[17,18] has resummed the leading infra-red singularities to all orders (in addition to the resummation of leading collinear singularities). In the soft region, interference contributions which contain infra-red logarithms in place of collinear ones, may not be neglected even in a physical gauge. Remarkably, despite the necessity of including interference graphs, a simple branching picture of jet development survives. It can therefore be easily implemented in a Monte Carlo program.[19] It is found that the opening angles decrease at every step in the branching process. The principal effect of this angular ordering is a strong suppression of the soft gluon component of the parton cascade. This suppression is a coherence effect due to the inability of a long wavelength gluon to resolve the colour charges of individual partons within the jet. As a consequence of the mistreatment of soft radiation,the Monte Carlo programs available for proton-proton collisions overestimate the growth of the parton multiplicity with jet energy. Unfortunately a complete Monte Carlo program with a correct treatment of soft radiation is not available for pp interactions. We therefore strongly suggest the development of such a program.

In an accompanying report[20] it has been shown that the traditional Monte Carlo approach using the leading pole approximation also mistreats the region of widely separated jets, which could be correctly taken into account by including the calculated $2\to3$ parton subprocesses.[21] Such widely separated jets are an important background to the decay into two jets of a new heavy object. The importance of the calculation of the $2\to4$ parton subprocesses was also emphasized.

In view of the predominant role which hadron hadron collider physics will play in the next two decades it was thought to be important that the existing calculations on the radiative corrections to $2\to2$ parton subprocesses[22] should be completed.

Conclusions

The need for efficient and practical Monte Carlo code which includes as much of the information which follows from perturbative QCD was the major conclusion of the jet working group. The predictions for SSC energies which follow from present Monte Carlo programs give disparate results. The physics above the hadronisation scale is a direct consequence of QCD and should be identical. It must be established whether any remaining differences correspond to alternative physical choices for the fragmentation or whether they are an unavoidable consequences of the large extrapolation in energy.

Acknowledgements

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7. J. Huston, "Comparison of the Predictions of Isajet and Fieldajet for Jet Structure at the SSC", contribution to these proceedings.
8. For insight to the low-x physics which may effect the general SSC event topology, see contributions by S. Ellis and J. Collins to these proceedings.
9. Data at a center-of-mass energy of 540 GeV from CERN give about 3 GeV per unit of pseudorapidity per 180 degrees of azimuth away from the jet axis. It is a very interesting question as to how much this background plateau will increase at the SSC.
10. The UA1 Collaboration has presented data on the observation of events with isolated leptons and jets consistent with a top-quark in the mass range 30-60 GeV/c^2. See, for example, the results presented by the UA1 Collaboration at The International Conference on Multi-Particle Dynamics, Lund (1984); Neutrinos '84, Dortmund; DPF Summer Study Snowmass (1984); and The XXII International Conference on High Energy Physics, Leipzig (1984).
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