MULTIPARTICLE DYNAMICS FROM 1983 TO 1993

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ABSTRACT

I compare our understanding selected topics in Multiparticle Dynamics at this meeting to what we knew at the 1983 Multiparticle Dynamics Symposium. I also discuss rapidity gap physics, a subject that has developed in the years since 1983.

1. Introduction

Ten years ago the XIV International Symposium on Multiparticle Dynamics took place at Lake Tahoe, California. In this year of 1993, we are met again at a beautiful mountain setting: Aspen, Colorado. At the 1983 conference several questions concerning the dynamics of elementary particles were of particular concern, and the participants looked to the future for a better understanding. That future is now. It thus seems a good opportunity to assess what answers we have found and what developments have played a major role in whatever progress has been achieved. I am afraid that I cannot project ten years into the future, particularly as the fate of the Superconducting Super Collider hangs in the balance, but we may be able to at least discern some directions along which the research frontier is yielding to determined efforts. I will concentrate on theoretical progress, but experimental developments will be necessarily intertwined with the story. Toward the end of the talk I will turn to the newly emerging question of rapidity gap physics, a question that was not contemplated in 1983.

I should point out that this talk will be a selection of just a few topics that seemed to me most interesting to discuss today, rather than a comprehensive review. I would have liked, for instance, to discuss the partonic structure of the photon, since this was an area of considerable interest at the 1983 conference and will, I think, be an area of substantial research progress in the next few years as a result of HERA experiments. Similarly, I would have liked to discuss
quark-gluon plasma formation in heavy ion collisions and its subsequent decay, possibly with temporary misalignments of the chiral pion and sigma fields from their vacuum values [1]. The reader will undoubtedly find some other favorite topic missing, but I hope that enough is left to capture his or her interest.

2. Beyond the Standard Model physics

The 1983 conference featured an excellent talk by J. Ellis [2] in which he advocated viewing multiparticle dynamics not as “an end in itself, but as a means for advancing to the next stage in physics.” He pointed out that “the Standard Model with its elementary Higgs fields may appear satisfactory at first sight, but it has problems” associated with its lack of explanation of why the mass scale of the Higgs sector is less than a TeV rather than the Grand Unified theory scale of some $10^{15}$ GeV or the Plank scale of $10^{19}$ GeV. Ellis’s favorite candidate for a theory beyond the Standard Model that solves this hierarchy problem was supersymmetry (SUSY). He urged the importance of searching for the expected supersymmetric partners of the quarks, leptons, gauge bosons, and Higgs bosons of the Standard Model.

Where are we today? We haven’t found SUSY. However, good chunks of the mass ranges for the expected particles have been explored. I would say that, given the negative results of this exploration, the prospects for supersymmetry being nature’s solution of the hierarchy problem are greatly diminished. I would say that, except that in ten further years of invention, we theorists have not been able to come up with a credible solution for the problem other than supersymmetry. Furthermore, during the last ten years, an exciting candidate for a theory of everything has emerged, the superstring theory. One cannot put much faith in this theory until it is well enough developed to produce quantitative predictions. However the case for supersymmetry is strengthened by the fact that supersymmetry is a natural feature of superstring theory. Another hint in favor of supersymmetry comes from grand unified gauge theory. In such a theory, the running values of the three couplings $g_i(\mu)$ of the Standard Model should reach the same value $g$ at the same value of the scale parameter $\mu$. With recent improvements in our knowledge of the value of the strong coupling $g_s(M_Z)$ from LEP, one can now see that this condition is not met by the Standard Model, but is met if the Standard Model is supplemented by supersymmetry with a symmetry breaking scale in a reasonable range, about 1 TeV [3]. So where are we today? We are still confused, but at a higher level.

3. Electroweak Standard Model physics

I now turn to Standard Model dynamics. 1983 was a watershed year for the Standard Model. On January 21 and 22, 1983, at seminars at the main auditorium at CERN, the UA1 and UA2 groups reported the experimental discovery of the W boson [4]. The discovery of
the $Z$ was announced by UA1 at a CERN seminar on 27 May and in a paper submitted to Physical Review Letters shortly thereafter. The accumulated evidence from UA1 was presented at the 1983 Multiparticle meeting in June in an exciting talk by E. Locci [5]. There were 52 $p\bar{p} \to W + X \to e + \nu + X$ events, 4 $p\bar{p} \to Z + X \to e^+ + e^- + X$ events and 2 $p\bar{p} \to Z + X \to \mu^+ + \mu^- + X$ events. From these, UA1 obtained the values shown in Table 1 for $M_Z$, $M_W$, and $\sin^2(\Theta_W)$, in good agreement with the expectations based on the Standard Model and low energy electroweak experimental results. They obtained $\rho \equiv M_W^2/(M_Z^2 \cos^2(\Theta_W)) = 0.925 \pm 0.05$, in agreement with the Standard Model value $\rho = 1$.

|        | 1983     | 1993     |
|--------|----------|----------|
| $M_W$ (GeV) | 80.9±3.4 | 80.47±0.3|
| $M_Z$ (GeV) | 95.6±3.3 | 91.187±0.007|
| $\sin^2(\Theta_W)$ | 0.226±0.016 | 0.2321±0.0006|

Table 1: Measured value of electroweak parameters in 1983 and 1993.

Measurements at LEP over the past four years have enormously increased the precision with which we have tested the electroweak sector of the Standard Model. This is illustrated by the 1993 values for $M_Z$ and $\sin^2(\theta_W)$ shown in Table 1, taken from the review of LEP results by S. L. Wu at this conference [6]. I also show the 1993 value for $M_W$, obtained from $\bar{p}p$ experiments at Fermilab [7]. You can see that the 1983 results were correct, within their errors. But what is really remarkable is how far the errors have been reduced. For $M_W$ the error has been reduced by a factor 10 (with further reductions in sight). For $M_Z$ the error has been reduced by a factor of 400 and for $\sin^2(\theta_W)$ by a factor of 30.

This improvement in precision is largely a story of accelerators and careful experiments, but substantial theoretical work has been required and has been carried out in order to match the experimental precision. We are now testing the theory at the one loop level. One significant result is that we can now give a value, with errors, for the top quark mass even though the top quark has not been directly seen. The value reported at this conference was $M_t = 166^{+17+19}_{-19-22}$ GeV [8]. Another significant result is that one can constrain the masses and couplings of possible new particles that might contribute to electroweak loop diagrams.

4. Focus on the strong interactions

In their Preface to the 1983 Proceedings [3], P. Yager and J. F. Gunion wrote

The symposium focused on the implications on tests of of quantum chromodynamics (QCD) over the full range of interactions: from low $p_T$ to high $p_T$; from $e^+e^-$
collisions to $\bar{p}p$ collisions; and from simple hadron-hadron collisions to nucleus-nucleus collisions. A principle aim of the conference was to increase our understanding of the extent to which non-perturbative effects such as confinement and final state fragmentation can, firstly, be isolated from hard processes so as to test perturbative QCD, and, secondly, be understood on the basis of QCD.

Indeed, if one overall conclusion can be drawn from the conference, it is that multiparticle dynamics must be still better understood both phenomenologically and theoretically before it will be possible to test in detail the correctness of QCD, either perturbatively or non-perturbatively.

I shall devote the next sections to a discussion of how well the aims articulated by Yager and Gunion have been realized during the past ten years. Briefly, it appears to me that we have done rather well on testing the correctness of QCD. We have done less well in understanding non-perturbative multiparticle phenomena on the basis of QCD, but I think there has been some progress.

5. QCD in $e^+e^- \rightarrow$ hadrons

At the 1983 Symposium, G. Wolf reviewed studies of the strong interactions in $e^+e^-$ annihilation experiments at PETRA and PEP. In particular, he focussed on the determination of $\alpha_s$ from these experiments. There is certainly more to testing QCD than simply measuring $\alpha_s$ in various ways and seeing if you get the same results within the errors. However, a comparison of such measurements in 1983 and 1993 can serve as an indicator of the development of the state of the art between these two times.

In Table 2, I show a selection of the results for $\alpha_s$ reported in Wolf’s talk. In each case I have used the renormalization group to translate from $\alpha_s(34 \text{ GeV})$ to $\alpha_s(M_Z)$. First is the value obtained from the total hadronic cross section. The theory for this quantity is simple, but the experimental errors are large. (This is because $\sigma_T \propto 1 + \alpha_s/\pi + \cdots$, so that a 2% measurement of $\sigma_T$ yields a 30% measurement of $\alpha_s$). Next I show the values obtained from various measures of the distributions of hadrons in the final state, i.e. the shapes of the events. The results depend on the fragmentation model used, either the independent fragmentation of each jet or the string model. These results were from the TASSO group. Finally, I show an analysis from the CELLO group based on the asymmetry of the energy-energy correlation function, which tells how the energy going in one direction is correlated with the energy going in a different direction as a function of the angle between the two directions. Again the results depend on which fragmentation model was used in the analysis.

In Table 3, I show values of $\alpha_s(M_Z)$ obtained by several different methods as of 1993. The values are taken from the review of I. Hinchliffe at the 1993 Rencontre de Moriond, except for the value for $\sigma_T(Z \rightarrow \text{hadrons})$, which changed significantly between spring and summer.
\[
\begin{array}{|c|c|}
\hline
\sigma_T(e^+e^- \rightarrow \text{hadrons}) & 0.15 \pm 0.05 \\
\text{shapes, independent jets} & 0.133 \pm 0.01 \\
\text{shapes, string fragmentation} & 0.165 \pm 0.01 \\
\text{AEEC, independent jets} & 0.105 \pm 0.01 \\
\text{AEEC, string fragmentation} & 0.119 \pm 0.01 \\
\hline
\end{array}
\]

Table 2: Measured values of \(\alpha_s(M_Z)\) in 1983 [9].

1993 and which I took from the talk of M. Shapiro at the 1993 Lepton Photon Conference [11]. Notice that there are a variety of methods used and that, in contrast to the situation in 1983, the values obtained using these methods agree within their errors.

\[
\begin{array}{|c|c|}
\hline
\sigma_T(Z \rightarrow \text{hadrons}) & 0.122 \pm 0.007 \\
\sigma_T(\tau \rightarrow \text{hadrons}) & 0.121 \pm 0.011 \\
\text{deeply inelastic scattering} & 0.113 \pm 0.006 \\
\Gamma(Y \rightarrow \text{hadrons}) & 0.121 \pm 0.008 \\
\Gamma(Y \rightarrow \text{hadrons}) & 0.108 \pm 0.010 \\
\hline
\text{Average} & 0.119 \pm 0.005 \\
\hline
\end{array}
\]

Table 3: Measured values of \(\alpha_s(M_Z)\) in 1993.

Considering just our example of \(e^+e^-\) annihilation, why do we seem to be doing better in 1993 than we were in 1983? One problem, which in fact received a lot of discussion in 1983, was the effect of non-perturbative, long-distance physics. This problem is reflected in the difference between the the independent jet model and the string model results. Partly we are better off now because of the higher \(\sqrt{s}\), 91 GeV versus 34 GeV on average. This makes the long-distance effects smaller (by a factor 3 or 9 depending on whether the effects go like \(m/\sqrt{s}\) or \(m^2/s\)). Partly we are better off now because of better Monte Carlo event generators, of which I will speak in a moment. Mostly, I think we are better off because of a better theoretical framework and better calculations.

**Calculations.** A serious confrontation between theory and experiment requires next-to-leading-order calculations (otherwise the theoretical errors are big and \(\Lambda_{\text{QCD}}\) isn’t really defined). These were becoming available by 1983, but there were disagreements among them. By now, there is a unified next-to-leading-order calculation by Z. Kunszt and P. Nason of all the suitable distributions describing the final state in \(e^+e^-\) annihilation [12]. This calculation, based on the 1980 matrix elements of R. K. Ellis, Ross and Terrano [13], agrees with most of the special cases in the previous literature.
**Theoretical framework.** In 1983 the difference between a measured quantity that is infrared safe (like the thrust distribution) and a quantity that is not (like the sphericity) was not understood. The essential idea had been introduced in specific cases in 1977 and 1978 by Sterman and Weinberg, by Basham, Brown, S. D. Ellis, and Love, and by Fox and Wolfram [14]. But the general principle had not really been absorbed. The quantities that are not infrared safe are sensitive to long distance effects like the splitting or joining of two collinear partons. They should not be used as a tool for examining short distance physics. Indeed, if you use next-to-leading-order perturbation theory to calculate an infrared unsafe quantity, you should get $\infty$. To avoid the infinities, you need to somehow insert a long distance model, and the result will depend on the model. In 1983, this was not understood, and infrared safe quantities were mixed with infrared unsafe quantities in the analysis.

Looking back on the 1983 results, one may speculate that it was not accidental that when an infrared safe quantity, the asymmetry of the energy-energy correlation function, was used in conjunction with the better fragmentation model (the string model), the result obtained for $\alpha_s$ was in good agreement with the present best value.

6. Improvements in Monte Carlo event generators

We have just seen an example in which Monte Carlo event generators have made a real difference. Such generator codes are now regarded as an essential part of particle physics experimentation and analysis. They were emerging as important tools around 1980 and advanced tremendously in power and usefulness in the period 1983 to 1993. Among the heros of this story are Paige and Protopopescu, Gottschalk, Andersson, Gustafson, Sjostrand, Ingelman, and Webber and Marchesini. Let me mention two of the important technical features that were introduced or received widespread implementation during this period [13].

**Hadronization schemes.** Two hadronization schemes are commonly used in the modern Monte Carlos. In the string picture, one imagines that color flux tubes (the strings) join outgoing partons; these strings then break into pieces with quarks and antiquarks at the newly formed string ends; these pieces become the final state hadrons. In the singlet cluster model, one imagines that each gluon splits into a quark-antiquark pair and one then finds low mass color-singlet clusters composed of the resulting partons. These clusters decay into hadrons. In each picture, there are adjustable parameters tuned to help fit the hadronization to experiment. In each picture, the hadronization is based on an approximation to the color flow in the perturbative process. Presumably this attention to the color flow accounts for some of the success of these schemes in fitting the data.

**Parton showers.** An essential feature of the Monte Carlos is their simulation of the decay of a far off-shell parton into two less far off-shell partons, and the subsequent decay of these partons into further partons, producing a parton shower. This simulation uses a small angle approximation to the tree level QCD graphs. The implementation of this showering
for incoming partons by means of so-called “backward evolution” is new since 1983, as is the approximate accounting for quantum interference embodied in “angular ordering.”

The best modern Monte Carlo event generators contain a great deal of information about QCD and soft multiparticle physics. They have become so good that there is a danger that experimentalists may mistake them for the Standard Model, forgetting that the programs actually contain an essentially tree level approximation to the Standard Model, mixed up with a of hadronization model that is tuned to experiment.

The Monte Carlos have become essential tools for a number of purposes. First, one can use a Monte Carlo to estimate Standard Model backgrounds for searches for new physics, being careful to keep track of where the approximations built into the program are good and where they are not. This is especially important in planning for future experiments. Second, one can use the programs to estimate the effects of detector resolution and efficiencies. There are inherent difficulties with this, since the Monte Carlo simulations are only approximate, but the results should be reliable as long as the correction applied to the raw data based on these simulations is small. Third, Monte Carlo programs can be used to estimate hadronization corrections to be applied to perturbative theory. One simply compares results with “hadronization” turned on and off. Evidently, this is a rather crude method, but in cases where hadronization effects are too large to ignore it is better than nothing. Finally, the Monte Carlos provide a way for experimentalists to explore the relation of their data to the underlying physical processes. Analytical calculations may provide a more accurate tool for special purposes, but such calculations cannot compete with the scope of the Monte Carlo method, which is able to simulate many different processes at once and to simulate whole events instead of just selected features of events.

What of the future? In my estimate, the power of the Monte Carlo method is potentially very great. One can imagine making the whole thing work at the N-loop level instead of the 0-loop (tree) level, putting more angular and spin information into the simulations, developing better descriptions of the hadronization, and so forth. Thus in 2003, the path theorists take between the fundamental Lagrangian and experimental predictions may always be paved with the blocks of a Monte Carlo program.

I have spoken of the use of Monte Carlo event generators to describe multiparticle dynamics in the case where there is a “hard interaction.” But there has been some success and there is great potential for understanding soft hadronic physics also. The potential is to model a very complicated process with hundreds of effective degrees of freedom using a simple underlying dynamics. One must be aware, of course, that the Monte Carlo method is adapted to the description of classical stochastic processes, whereas Nature uses quantum probabilities rather than classical probabilities. Thus the method may be applied if there is a choice of variables for which a semiclassical description works. These variables may be the coordinates or the momenta of quarks and gluons; the coordinates or the momenta of pions and rhos; the
configurations of color flux tubes, or other possibilities. In this view, the art of modelling hinges on the choice of variables.

7. Parton distribution functions

Knowledge of parton distributions is essential for making predictions in processes with one or two hadrons in the initial state. One needs this knowledge both for making predictions based on the Standard Model and for predictions based on extensions to the Standard Model such as supersymmetry. Thus, for instance, in 1983 one needed to know the distribution of quarks in the proton in order to predict the cross sections for $W$ and $Z$ boson production.

Today, one determines the distribution functions for all the partons at once in a global fit of data from many processes, as described by J. Morfin at this conference [16]. In 1983, the science of making such global fits was just beginning. One had the fits of Buras and Gaemers [17]. In 1983 the first of the Duke-Owens fits was produced [18], along with the fit of Eichten, Hinchliffe, Lane and Quigg [19]. In 1993, the available fits are much more accurate. First, the data are better. Second, the theory is better. Next-to-leading order calculations are used for the theoretical cross sections that are compared to the data used in the fit; next-to-leading order parton evolution is used. Currently there are two families of parton distribution sets that are regularly updated by their authors to take into account data as it becomes available. These are the sets by Martin, Roberts, and Stirling [20] and by the CTEQ Collaboration [21]. We will see an example in the following section of how better parton distributions have helped improve predictions.

8. Jet production in hadron collisions

In 1982, the UA2 group demonstrated the existence of clearly visible jets in proton-antiproton collisions at the CERN collider. Jets had been seen and studied in electron-positron collisions, but it had been uncertain whether they would be a useful tool for examining quark and gluon interactions in the more complicated environment of hadron collisions at the CERN collider energy. The following quote from J. Hansen, representing UA2 at the 1983 Multiparticle Conference summarizes their observation [22]. “The cross section for jets with a given transverse energy is much larger at the $p\bar{p}$ collider than at the ISR. At large energies jets are clearly visible, there is no need for an elaborate algorithm to separate jets from the background. This is clearly seen in fig. 3a, which is a LEGO-plot of the energy distribution in the $\phi, \theta$ plane for the event with the highest transverse momentum.” Figure 3a from that talk, not reproduced here, was a plot in the now-familiar Lego format showing two distinct jets of about 80 GeV transverse energy each.

At the 1993 Multiparticle conference both the UA1 and the UA2 groups gave talks on jet production. I consider here the simplest of their results, the one jet inclusive cross section
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Figure 1: Inclusive jet production cross section presented by the UA2 Collaboration at the 1983 Multiparticle Conference [22]. The error bars include the statistical and the $E_T$ dependent systematic errors. One should add a 40\% $E_T$ independent systematic error. The two curves A and B represent the QCD prediction.

$d\sigma/dE_T d\eta$ to make a jet with transverse energy $E_T$ and rapidity $\eta$, at $\eta = 0$. I reproduce in Fig. 1 the results presented by UA2. The two curves A and B represent the QCD prediction. As you can see, the theoretical prediction has an uncertainty of about a factor 3 either way from the midpoint between the two curves. This uncertainty was reported to arise from the uncertainty in the parton distributions used in the calculation.

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Figure 2: Inclusive jet production cross section presented by the CDF Collaboration at the 1983 Multiparticle Conference [23]. The error bars include the statistical errors only. The curve represents the next-to-leading-order QCD prediction [24].

Where are we now? I display in Fig. the result of the CDF group for $d\sigma/dE_T d\eta$ averaged over a range of $\eta$ near $\eta = 0$ [23]. The systematic errors, not shown in the figure, have been
substantially reduced, to something like 30%. At the same time, the range of $E_T$ covered has substantially increased. The plot also shows the prediction of QCD [24]. The largest theoretical uncertainty (not displayed) arises from the uncertainty in the parton distribution functions (together with $\alpha_s$), which is estimated [24] to be about 20%. This is a graphic illustration of the improvement in our knowledge of parton distribution functions. There is also a substantial uncertainty from truncating the perturbative cross section at a finite order of perturbation theory. In this case, the leading order and the next-to-leading order contributions are included, and the uncertainty from omitting next-to-next-to-leading order terms may be estimated to be about 15% [24]. In the case of the 1982 curves, which were leading order, one might have estimated a 50% uncertainty from not including next-to-leading order. In summary, both experiment and theory have improved, so that one can now compare the two with a combined uncertainty of perhaps 50% over an $E_T$ range over which the cross section changes by nine orders of magnitude. Thus there has now been a good chance for Nature to prove QCD wrong.

9. Lattice QCD

At the 1983 Multiparticle conference, H. Quinn presented a talk titled “A word of caution” warning against overconfidence in perturbative QCD. During the discussion period after the talk, the following exchange occurred.

J. Rushbrook (Cambridge): For a specific theory to be useful, it has to be falsifiable, i.e., we have to be able to know when it fails. Does QCD satisfy that criterion?

Quinn: Not yet.

Rushbrook: Will it ever? Will we know that it will?

Quinn: I don’t think we will know it from jet physics. I think if we know it we will know it because we keep trying to do some hard calculations in QCD and get to the point that perhaps eventually we will have non-perturbative methods that will calculate the hadron spectrum in QCD. After all it’s supposed to be the fundamental theory of hadrons; it ought to calculate a few fundamental parameters, like the mass of the proton over the mass of the rho. Those are the things that are the real tests of QCD.

Today lattice QCD had made great strides. Much of the development has been in the direction of calculating hadronic matrix elements of weak decay operators. However, I would like to focus on an example along the lines suggested by Quinn: the calculation of hadron masses in the valence approximation reported this year by Butler, Chen, Sexton, Vaccarino, and Weingarten [25].
|                | Calculated         | Measured |
|----------------|--------------------|----------|
| \(M(N)/M(\rho)\) | 1.219±0.105        | 1.222    |
| \(M(\Phi)/M(\rho)\) | 1.333±0.032        | 1.327    |
| \(M(\Delta)/M(\rho)\) | 1.595±0.111        | 1.604    |
| \(M(\Omega)/M(\rho)\) | 2.298±0.098        | 2.177    |
| \([M(\Xi)+M(\Sigma)-M(N)]/M(\rho)\) | 1.930±0.073        | 2.047    |

Table 4: Calculated values of ratios of hadron masses to the mass of the \(\rho\) meson, from Weingarten et al. [25]. There are also predictions for \(M(K^*)/M(\rho)\), \(M(\Sigma^*)/M(\rho)\), and \(M(\Xi^*)/M(\rho)\), but these may be viewed as being involved in the fitting for the quark masses rather than being independent predictions.

In this calculation, we lack numerical control on how good the valence approximation (no quark loops) is. However, the other approximations are controlled. For example, the simulated hadrons are in a universe of finite size not much bigger than a hadron size; the distance between neighboring lattice points is not zero; chiral symmetry is broken by the lattice approximation and must be restored. The authors attempt to correct for these approximations and estimate the error involved in doing so. Their results, with errors, are shown in Table 4. One should note that if the results did not match experiment, we could blame the valance approximation instead of the fundamental theory. Nevertheless, the results go a long way toward answering Quinn’s challenge.

10. Multiparticle correlations

At the 1983 Multiparticle Conference, there was considerable discussion of the distribution of particles produced in soft hadron collisions (without high transverse momentum jets) [26, 27]. The participants were interested in the average number of particles per unit rapidity, \(dN/dy\), the probability to get a given total multiplicity, \(P(N)\), correlations between the numbers of particles with large positive rapidity and large negative rapidity \(y\), the distribution of electric charge as a function of rapidity, and so forth. Models such as the Dual Parton Model [28] were proposed to explain the data, while too-simple models were ruled out. However, most models survived, as reflected in the following quote from the introduction to the talk of E. A. De Wolf [27]. “Many models have been proposed and were found to be overall quite successful. Because of large differences in their dynamical input at the ‘microscopic’ level . . . it has come as a surprise that essentially all models agree with most of the data examined.”

In the years since 1983, the examination of multiparticle distributions has become more exacting. Thus at the 1993 conference there was much emphasis on examining the correlations between particles with small separations in \(y\) and \(\phi\). One is finding that correlations exist
on all scales of $\Delta y$, $\Delta \phi$ down to quite small values. A favored method for looking for these features of the data uses intermittency analysis [29], but other measures were discussed as well.

The remarkable fact, which serves as an indication of progress, is that this increasingly sophisticated experimentation and data analysis is proving capable of challenging the models. Thus, for instance, the Dual Parton Model, although it gets the gross features of multiparticle production right, does not correctly reproduce the intermittency behavior displayed by the data [30].

11. Rapidity gap physics

I now turn to a subject that is both old and new, rapidity gaps in scattering events. This subject can be introduced by considering elastic scattering, a venerable topic that was discussed at the 1983 multiparticle conference. We consider elastic scattering of two hadrons at large $s$, small $t$, as depicted in Fig. 3. (Diffractive dissociation events are similar, but I do not consider them here.) A plot of transverse energy deposition in the calorimeter versus azimuthal angle $\phi$ and (pseudo-)rapidity $\eta$ for elastic scattering is very simple, as shown in Fig. 4. Hadron A appears in the final state at large positive rapidity $\eta \approx \frac{1}{2} \ln(s/|t|)$, while hadron B appears at large negative rapidity $\eta \approx -\frac{1}{2} \ln(s/|t|)$. In a typical hadron scattering event, the calorimeter is full of particles covering the whole range of pseudorapidities. In an elastic scattering event, there is a large gap in the rapidity space in which there are no particles.

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\texttt{Figure 3: Elastic scattering.}

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\texttt{Figure 4: Elastic scattering transverse energy deposition versus $\eta$ and $\phi$.}

The quantum system exchanged between the hadrons in elastic scattering at large $s$ and small $t$, represented by the jagged line in Fig. 3, is called the pomeron. There was considerable discussion of the nature of the pomeron at this conference [31]. The best current analyses involves sums of diagrams like that shown in Fig. 5, together with more complicated diagrams. In this picture, I have endeavored to depict the time evolution, with gluons emitted from the hadrons long before the scattering and being absorbed into the hadron state long afterwards. The theoretical questions being addressed in current studies of the pomeron are difficult, and it is not easy to follow the details, but the physical picture of interacting gluon clouds, as illustrated in Fig. 5, may be helpful as a guide to understanding.

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The simplest perturbative version of pomeron exchange is the scattering of two partons by exchange of two hard gluons, as depicted in Fig. 5. Here we ask that $\hat{s} \gg |\hat{t}|$ and that the exchanged gluons form a color singlet. We also ask that $\hat{t}$ be large compared to $1 \text{ GeV}^2$, and indeed that both gluons carry large transverse momentum, so that we are describing a short distance process. If, in a hadron-hadron scattering event, two partons scatter as in Fig. 6, the outgoing partons will show up as high $p_T$ jets, separated in rapidity by $\Delta \eta \approx \ln(\hat{s}/|\hat{t}|)$. If nothing else happened in the event, there would be no particles produced in the gap between the two jets. Bjorken has argued [32] that even allowing for the other things that can happen, there is still a not-tiny probability for this gap to survive. (If this is so, then there will be applications for other hard scattering processes with color singlet exchange, such as Higgs boson production at the SSC.) One process that is sure to happen is gluon bremsstrahlung from the scattered partons. One expects collinear radiation along the beam directions and along the jet directions. One also expects soft radiation into the regions between the jets and the beams. That is, if the forward parton is scattered to angles $(\eta_1, \phi_1)$, then one expects radiation near $\eta = \eta_1$, $\phi = \phi_1$, near $\eta = \infty$, and in the range $\eta_1 < \eta < \infty$. Similarly, there will be radiation near $\eta = \eta_2$, $\phi = \phi_2$, near $\eta = -\infty$, and in the range $-\infty < \eta < \eta_1$. However as long as the scattering was accomplished by a hard color singlet exchange, there is no bremsstrahlung in $\eta_2 \ll \eta \ll \eta_1$. The gap remains. One must now ask if soft collisions between the remaining quarks from the two hadrons will produce particles in the whole calorimeter, thus spoiling the gap. The probability that spectator collisions do not fill the gap is tentatively estimated as a few percent [32]. The event structure for events with surviving gaps is illustrated in Fig. 7.

At this meeting, the D0 group at the Fermilab Collider reported seeing events with the signature indicated in Fig. 7 [33].

There is another kind of gap event that was anticipated for deeply inelastic scattering events at HERA. However, here the underlying physics is quite different. Consider a deeply inelastic electron scattering event in which $x_{bj} \ll 1$. A typical Feynman diagram representing...
such an event is shown in Fig. 8. The struck quark is scattered through a large angle and emerges as the “current jet” with rapidity $\eta_J$. The proton remnants have large positive rapidity and produce particles in the calorimeter near $\eta = \infty$. This struck quark, which carries a small fraction $x_{bj}$ of the proton’s momentum, is produced by the successive splitting of partons carrying larger momentum fractions. In the diagram, the partons enter the final state. They fill the calorimeter at rapidities between $\eta_J$ and $\infty$. However, it is possible for most of the gluons in the diagram to recombine with the valence quarks of the proton and thus reconstitute the proton, as indicated in Fig. 9. One might call this recombinant bremsstrahlung. The proton enters the final state having lost a small fraction ($> x_{bj}$) of its longitudinal momentum and having a small amount of transverse momentum transferred to it. This phenomena, called diffractive hard scattering, or diffractive deeply inelastic scattering in this case, was anticipated by Ingelman and Schlein [34]. As is suggested by the diagrams, the phenomenon is similar to elastic scattering, but with the pomeron probed by the hard virtual photon.

In diffractive deeply inelastic scattering, one should see the elastically scattered proton at large rapidity but with a large gap around $\eta = \infty$, as shown in Fig. 10.

Diffractive hard scattering can also been seen in hadron-hadron collisions. Here the hard scattering is parton-parton scattering to produce jets. If the jets are produced by collision of a small $x$ parton from one of the hadrons, then the partons that carry most of that hadron’s momentum can recombine so that the hadron appears again in the final state, having lost a small fraction $z$ of its longitudinal momentum. This is depicted in Fig. 11. Again, there is a gap, as sketched in Fig. 12. This type of event was predicted in [34] and seen by the UA8 experiment at the CERN collider [36].

I would like to point out a feature of hard diffractive scattering that I am currently studying with A. Berera [37]. In Fig. 11 one gluon from the pomeron participates in the hard
scattering, while one enters the final state. Of course, more than one gluon could have been emitted. There must be at least one “extra” gluon because the pomeron carries zero color charge, while the gluon that participates in the hard scattering is a color octet. The extra gluon in Fig. 11 carries away the extra color charge, and it also carries away some longitudinal momentum. Thus the momentum fraction $x$ delivered to the hard interaction is less than the momentum fraction $z$ carried by the pomeron. However, there is another possibility. The extra color can be transferred to the spectator partons of the oppositely moving hadron as shown in Fig. 13. The gluon exchanged in this process carries negligible longitudinal momentum. Such graphs exist in normal hard processes such as jet production, but their effect cancels because of unitarity. Here the unitarity argument does not apply because one is not summing over all final states, but rather is demanding that the initial hadron emerges again, slightly scattered, in the final state. This sort of violation of the normal hard scattering factorization has also been studied by Collins, Frankfurt, and Strikman [38]. There is some evidence in the experimental results of UA8 [36] that for many of the events $1 - x/z$ is small, indicating either that the “extra” gluon(s) in Fig. 11 are often quite soft or that the graphs like those in Fig. 13 are important. In either case, it would appear that the same effect should not be seen in diffractive deeply inelastic scattering: in deeply inelastic scattering the “extra” parton is a quark, which does not like to be soft.

12. Conclusion

I have tried to compare where we are now in the study of multiparticle dynamics compared to where we were at the time of the 1983 conference. Naturally, I have only been able to touch on some selected topics for this comparison. Nevertheless, I have personally found it to be an instructive exercise. I have found the evolution of the field to be a little like a hike in the mountains surrounding Aspen. It often seems as though you are moving slowly, considering how far there is to go, but if you stop to look back you can see that you have covered more
ground than you thought.

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