STATUS OF MULTIPARTICLE STUDIES

L. Van Hove
CERN - Geneva

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LIST OF UNCOMMON ABBREVIATIONS

CM : centre of mass
DPM : Dual Parton Model
HH : hadron-hadron
IP : impact parameter
LH : deep inelastic lepton-hadron
LM : Lund Model
MD : multiplicity distribution
MPP : multiparticle production
NB : negative binomial
NBMD : negative binomial multiplicity distribution

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1. AIM, CHARACTERISTICS AND PRESENT STATE OF THE FIELD

1.1 The Aim

The last four decades have seen spectacular advances in particle physics, leading to what is commonly called the Standard Model. Despite obvious theoretical shortcomings, this scheme is enormously successful in describing the experimental facts on all processes where it is able to make specific predictions, and the variety of these processes is very great indeed. The strong interaction sector of the Standard Model, in particular QCD (Quantum Chromodynamics) which is the gauge field theory of quarks and gluons, has been confirmed by many tests in hadron-hadron (HH), deep inelastic lepton-hadron (LH) and e±e⁻ annihilation collisions at high energy. All the quantitative tests are based on perturbative predictions of QCD, the only ones which can be reliably calculated so far, and they therefore concern hard processes.

The main research frontier of strong interaction physics is now moving to the non-perturbative sector of QCD, where the most fundamental problems are the colour confinement mechanism and the structure of the vacuum. Hadron spectroscopy and multiparticle production (MPP) are the two main domains where this research can be pursued. While new data on hadron spectroscopy are very hard to get, practically all high energy experiments can give abundant information on MPP. The central aim of MPP studies is to construct a unified QCD-based description of HH, LH and e⁺e⁻ processes, and to use it as a tool for unraveling the non-perturbative sector of QCD.

As illustrated also in the Workshop, some people study MPP without invoking QCD, e.g., in quantum optical or purely statistical approaches. Although these investigations can be very interesting, it seems to me that they miss the central issue. In my opinion, we have now reached a stage where studying MPP without QCD is like studying superconductivity without the Schrödinger equation.

1.2 Characteristics and Present State of MPP Studies

Just like in superconductivity, a central difficulty of MPP lies in the great complexity of the experimental facts. The situation is worse, however, because in MPP we do not have any equivalent to
the BCS (Bardeen-Cooper-Schrieffer) theory which describes low temperature superconductivity very successfully. We are in about the same situation as solid state physicists in pre-BCS days, when many tentative models of superconductivity were on the market. It is interesting to note how rapidly such a confusion may disappear, as happened with the discovery of Cooper pairing of electrons which led to the BCS scheme.

It is obvious that this has not yet happened for MPP, and we have to live further with a variety of competing models, each rather vague in some of its concepts and rather flexible in some of its assumptions and/or approximations. In the present stage of development it is unreasonable to demand (as was done repeatedly in the general discussion session of the Workshop) that this lack of precision should be lifted: it is perfectly normal for the details of the models to evolve from year to year under the influence of new experimental facts, and one can safely predict that the most inflexible theorists will not be the most successful ones.

One further characteristic of MPP is that there are no natural collective variables which are directly measurable (as are the thermodynamical variables and transport coefficients in condensed matter physics). This implies that, for many purposes, model work is only useful when it involves the Monte Carlo generation of full collision events. Reading the published description of such computer codes (see ref.1 for an example) illustrates both the complexity and the flexibility of the models.

To a large extent, the present models are tentative theoretical descriptions of complex phenomena, and their usefulness for experimental physicists is often linked with their practical descriptive value more than with their ability to make firm and precise predictions. It is difficult to regard this type of work as fundamental and, consequently, its interest is often rated rather low in the high energy physics community. We have to accept this judgment until some "BCS type" breakthrough is finally achieved. In the meantime, it would help the credibility of the field if once in a while theorists would agree that some particular line of model making lacks success and/or usefulness.
This is of course not to say that research on MPP should not be vigorously continued, nor that model-makers should protect themselves by shunning predictions. In addition to the great help which the best models bring to the experimentalists, the central aim is to find the proper theoretical tools for non-perturbative QCD and to contribute thereby to the understanding of confinement, which is the most novel and perhaps the most profound property embodied in the Standard Model.

The present text goes somewhat beyond my closing talk at the Workshop. It incorporates a brief summary of my own contribution on multiplicity distributions in a QCD parton shower model of $e^+e^-$ annihilation, and it includes a few points which were not covered in my oral presentation.

2. THE KNO SCALING DEBATE

The KNO scaling law played a very important role in the study of multiplicity distributions (MDs) since the time of its formulation in 1972. It was derived by Koba, Nielsen and Olesen on the basis of the assumption of Feynman scaling. Surprisingly, while the latter turned out very soon to be violated by the data, KNO scaling did empirically very well up to ISR energies (centre-of-mass energies $E_{CM} \leqslant 63$ GeV), especially in the modified form due to A. Golokhvastov (see ref.2 for a recent analysis). Then came the surprise of its clear violation at the CERN $\bar{p}p$ collider\(^3\) and its replacement by another empirical law, the negative binomial (NB) form of MD (see section 5).

As was apparent at many meetings including this Workshop, the reactions of theorists were divided. One attitude is to say that a new regime sets in somewhere in the range $E_{CM} = 60-200$ GeV, and indeed the appearance of signs of semi-hard processes (minijets) at the CERN collider ($E_{CM} = 200-900$ GeV) can be invoked as the origin of KNO scaling violation (see R. Hwa's contribution on this subject). This would be an attractive approach if KNO scaling in absence of minijets would follow naturally from soft collision dynamics, which is not the case as far as I can see.
The opposite attitude (which I favour) is to say that there is no theoretical basis for KNO scaling and to notice with the UA5 Collaboration\textsuperscript{3}) that its occurrence up to $E_{CM} = 63$ GeV can be understood from the observed energy variation of the NB parameters over the range $E_{CM} = 10$–546 GeV (as explained by G. Ekspong at the Workshop, the situation for total multiplicities is unclear at the top collider energy, $E_{CM} = 900$ GeV). In other words, KNO scaling can be regarded as an approximate and transient behaviour disappearing at higher energies.

3. THE IMPACT PARAMETER DEBATE

There is another debate in MPP dynamics which is also undecided. For decades, theorists held divergent views on the importance of impact parameter (IP) considerations for describing and understanding MPP, and no resolution of the dilemma is in sight for particle-particle collisions. Quite remarkably, however, seventeen days of oxygen beam time (beam energy 60 and 200 GeV per nucleon) at CERN late in 1986 were enough to prove beyond any doubt that IP considerations are essential to describe ultra-relativistic $^{16}$O collisions with heavy nuclei. This is strikingly demonstrated by the shapes of the observed transverse-energy distributions in comparison with those for pp and for p-nucleus collisions\textsuperscript{4}).

For particle-particle reactions, it is often argued that it is the IP which makes the main difference between HH collisions and $e^+e^-$ annihilation, providing a neat explanation for, e.g., the long-range forward-backward multiplicity correlations present in HH and absent in $e^+e^-$. This is not conclusive, however, because IP considerations can be replaced by momentum transfer considerations. For example, a large longitudinal momentum transfer in the initial HH interaction (which could be gluon exchange) will tend to excite strongly both hadrons, inducing a substantial forward-backward correlation. In fact, IP considerations play only modest roles in the best models now available for soft HH collisions, the Dual Parton Model and the Lund Fritiof Model.
As to the vanishing of the IP in $e^+e^-$ annihilation, we now know that it does not prevent single events to have a very narrow jet structure which QCD explains quite naturally by the initial materialization of the virtual photon in a quark and an antiquark which fly off back-to-back with great energy before they hadronize. That the original $q\bar{q}$ system has total angular momentum 0 or 1 seems to be of little consequence for the MPP process.

In addition, since the introduction of the Pomeron exchange concept for soft HH collisions, the "IP debate" even extends to small angle elastic scattering, the diffractive nature of which suggests most naturally an IP description. The importance of the exchange mechanism approach is emphasized by the continued shrinking of the diffraction peak observed up to the highest collider energies.

4. DUAL PARTON MODEL VERSUS LUND MODEL

Whoever follows the field of MPP will be struck by the dominant position occupied by two theoretical models, the Dual Parton Model (DPM) and the Lund Model (LM). This has been illustrated at the Workshop by the many contributions of A. Capella for DPM and B. Andersson for LM, also by the lively discussions on the pros and cons of each approach.

Although the two models are in clear competition for soft (low $p_T$) hadronic processes, they now have more in common than before, because the present LM for soft HH collisions (called Fritiof) strongly resembles DPM for the two fragmentation regions. This regions are populated by the fragmentation of two strings, one for each hemisphere. The strings are attached to the two energetic di(quarks) which are producing the leading particles. The models differ in the central region, by the way the two strings attach to the remaining partons (in DPM they cross over from one incident hadron to the other whereas in Fritiof they don't) and by the fact that DPM has additional strings in the central region. The first difference might manifest itself experimentally by its effect on the charge transfer between the two hemispheres, but the difference is very small and probably beyond the limit of precision one may expect from such models. Fur-
thermore, in both models the strings are assumed not to interact with each other although they overlap in the central region. This assumption may have to be relaxed, which would decrease the distinction between the two models. We heard also from W. Kittel's contribution that both models tend to underestimate the central multiplicities (NA22 Collaboration experiment at $E_{CM} = 22$ GeV), so that their treatment of the central region will evolve further.

Such evolution is in fact already going on because both models begin to incorporate semi-hard processes capable of producing mini-jets. This requires in DPM to give a dynamical role to gluons (which were left out altogether until now). Since gluon effects are already important in Fritiof for central multiplicity reasons, we see again converging trends.

At a broader level, however, there remains the fundamental difference that Fritiof is only one part of the LM, the other parts describing one-string processes like $e^+e^-$ annihilation and LH deep inelastic scattering, and doing this with great success. In contrast, DPM has nothing to say on these processes; in fact the string fragmentation rule of DPM is now simply taken over from the one-string versions of LM. Among the latter, the program JETSET\textsuperscript{1}) provides at present the best description of $e^+e^-$ annihilation, as was shown in ref.5 by a thorough comparison with available competitors.

As I said before, the current evolution of DPM and LM goes in a direction of convergence, with a growing role and a better description for the gluonic component of QCD, and with inclusion of a smooth transition to semi-hard processes (on the latter topic see also ref.6). In my opinion, the main task now is to pursue this road to a common comprehensive model description. In the mean time, it should be clear that it is pointless to ask for a detailed, "frozen" description of DPM, Fritiof, JETSET, or any other model on the market.

5. THE NEGATIVE BINOMIAL ENIGMA

5.1 General Considerations

As abundantly illustrated in the experimental contributions to the Workshop, a large number of multiplicity distributions (MDs)
for full phase space and central rapidity windows are very well described by the negative binomial (NB) probability law, which has a simple mathematical structure in terms of its generating function

$$F_{NB}(z) = \sum P_n z^n = \left[1-\left(\bar{n}/k\right)(z-1)\right]^{-k}$$

where $\bar{n}$ is the mean multiplicity and $k$ is linked to the dispersion:

$$\left(n^2-\bar{n}^2\right)/\bar{n}^2 = (1/\bar{n})+(1/k)$$

The wide success of NB fits for HH, LH and $e^+e^-$ processes is a striking empirical fact (see ref.7 for a recent review). It is very convenient for describing data and extrapolating them to higher energies, because the NB depends only on two parameters and both turn out to vary quite smoothly with the energy and the rapidity window.

What is more difficult is to give a dynamical explanation for the NB behaviour of MDs in MPP. Keeping in mind that NBMDs occur in many statistical data outside of high energy physics (biometrics, insurance risks, quantum optics, cascade processes,...), one should not be surprised if the explanation were not unique. In fact, as time goes on, a growing number of MPP models are able to reproduce the NB shape of MDs (although they did not predict it). The basic reason for the wide occurrence of NBMDs is that these distributions are characterized by the simplest form of growth of the ratio

$$g_n = (n+1)P_{n+1}/P_n$$

namely linear in $n$ (a constant ratio gives a Poisson distribution corresponding to independent emission). Whenever MDs of particle-particle collisions are negligibly affected by conservation laws, they appear to have this linear increase of $g_n$ with $n$ (for HH collisions single diffraction dissociation must be separated out). The situation is different for nucleus-nucleus collisions, where the shape of the MD is profoundly modified by the averaging over the impact parameter (similarly to what happens with the transverse energy distribution, see section 3, end of first paragraph).
5.2 A Monte Carlo Experiment

As mentioned earlier, the Lund program JETSET\textsuperscript{1}) does an excellent job in describing the existing $e^+e^-$ annihilation data\textsuperscript{5}). Extending earlier work of W. Kittel\textsuperscript{8}), A. Giovannini and I studied the MDs predicted by this model (more precisely the version called Lund Shower Model in ref.\textsuperscript{5}) for $E_{\text{CM}}$ ranging from 22 to 2000 GeV, not only for the charged hadrons but also for the final partons, i.e., for the quarks, antiquarks and gluons present when the hadronization phase of the program sets in. In addition to the $q\bar{q}$ system relevant for $e^+e^-$ annihilation, we also studied the gluon-gluon system at the same $E_{\text{CM}}$. While I presented preliminary results in a separate lecture at the Workshop, a complete report is now available\textsuperscript{9}). Here I give only a summary.

Both the hadronic and partonic MDs for full phase space and in symmetric rapidity windows are found to have NB shape with properties analogous to those observed in HH, LH and $e^+e^-$ experiments. In addition, we found the following relations between the NB parameters of the hadronic and partonic distributions:

$$ n_h \approx C n_p , \quad k_h \approx k_p $$

with $C \approx 2$ for all rapidity windows and full phase space. As explained in ref.\textsuperscript{9}, the above relations can be linked to the concept of local parton-hadron duality\textsuperscript{10}).

The study of ref.\textsuperscript{9} also throws new light on the "clan" structure of NB distributions. This structure is mathematically defined by the property that a NBMD can always be constructed as a Poisson distribution of clusters (which we call clans), with a logarithmic MD for the average clan. The mean number of clans is $\bar{N} = k \ln(1+\bar{n}/k)$ and the mean clan multiplicity $\bar{n}_c = \bar{n}/\bar{N}$. The Lund Shower Model reproduces for the $q\bar{q}$ and the $gg$ systems the surprising result of the HH experiments: for fixed rapidity window $\bar{N}$ remains almost constant over the wide energy range studied, the multiplicity growth being mainly due to the increase of $\bar{n}_c$. At partonic level, the analysis of our "Monte Carlo experiment" leads to a new, approximate but physically intuitive picture of the clan structure: the partonic clans
can be pictured as being dominantly bremsstrahlung gluon jets (mostly rather soft) with a geometric MD, which by averaging reproduce the logarithmic MD mentioned above. This geometric MD of the partonic clans is very natural in a shower model because it corresponds to the simplest case of self-similar cascade (see ref.9 for details).

The large extent of common behaviour found in the clan analysis of HH, LH and e⁺e⁻ processes⁷,⁹) leads us to suggest that the above interpretation of clans as bremsstrahlung gluon jets with geometric MD should be included in the future "comprehensive model description" called for at the end of the previous section. It should be clear, however, that we are still far from a true theoretical understanding of the NB properties of MDs, even in the Monte Carlo experiment just reviewed; one should indeed elucidate mathematically why the quite sophisticated Lund Shower Model leads to such simple properties of the partonic MDs, the non-perturbative transition to the hadronic level being then taken care of by the local parton-hadron duality principle as expressed in ref.9. Consequently, as of today, there is in my opinion no such thing as an established "negative binominal model" or "clan model" for MPP (which does not prevent the NB properties and the related clan structure to offer powerful tools of empirical and theoretical analysis). Hence the title "Negative Binomial Enigma" which I chose for this section.

5.3 The Laser Distribution

I end with a remark concerning parametrizations of MDs which are more general than the NB. The most popular one is the Glauber-Lachs-McGill-Peřina distribution, also called partially coherent laser distribution, which involves three parameters¹¹). The general experience has been that it is difficult to determine all parameters uniquely from the data and that the quality of fit is not much improved compared to the two-parameter NB. This is confirmed by a very recent study of C. Fuglesang¹¹) based on the UA5 Collaboration data at $E_{CM} = 546$ GeV.
6. SOME "EXOTIC" TOPICS

This section treats three topics which fall somewhat outside the main research lines on MPP.

6.1 Emission of Soft Positrons in Hadronic Collisions

In a recent analysis of an ISR experiment, the Axial Field Magnet Collaboration found a remarkable property of the $e^+/e^-$ charged pion ratio at low $p_T$\textsuperscript{12). In the rapidity region $|y|<1$ and for $p_T$ up to $0.4$ GeV/c, this ratio turns out to be proportional to the number of charged pions, or equivalently, the number of low $p_T$ positrons (and surely also electrons) grows like the square of the number of charged pions. This supports production mechanisms\textsuperscript{13} where the number of pions grows proportionally to the number $n_q$ of quarks produced in the central region, whereas the number of $e^+e^-$ pairs grows like $n_q^2$, i.e., like the number of quark-antiquark pairs. It is, however, also compatible with E.L. Feinberg's older suggestion that the $e^+e^-$ pairs could be produced in the hadronic phase of the collision, e.g., by pion-pion annihilation\textsuperscript{14}. This very interesting topic clearly deserves further experimental and theoretical work.

6.2 Spikes in Rapidity Distributions

Spikes, i.e., large concentrations of particles in small (pseudo-)rapidity intervals, have been seen in many cosmic ray experiments, and also in the UA5 streamer chamber experiment at the CERN collider. A spectacular event of this type was recently found by the NA22 Collaboration in a $\pi^+\pi^-$ collision at $p_{\text{lab}} = 250$ GeV\textsuperscript{15). It has 10 charged particles in the CM rapidity window $-0.24<y<-0.14$. The probability that this anomalous event is a fluctuation is estimated to be of order $10^{-3}$, and further events of this type would have to be found before one can assert their significance.

It is nevertheless interesting to speculate on the physical meaning which the NA22 spike could have if it were significant. While the enormous local particle density in rapidity ($\sim 100$) suggests a very hot spot (Bjorken's well known estimate of energy density would give $\sim 7$ GeV/fm$^3$ at time $1$ fm/c after the beginning of the collision), one must realize that, on the contrary, one may have to do with a "large" piece of cold hadronic matter. In fact, in the rest
frame of the spike, all 10 particles have very low longitudinal momenta ($\lesssim 10$ MeV/c if they are pions), so that by applying the uncertainty principle one would deduce that they originated from a source region measuring some 20 fm in the longitudinal direction! As to the transverse diameter of the source region, it could measure 1 to 2 fm because the $p_T$ vectors of the 10 particles are distributed normally in length and azimuth.

How could such a cold elongated source region come about? Could it be created by the QCD string network which must necessarily appear when a dense cloud of partons expands rapidly$^{16}$? This is perhaps not impossible if the energy of longitudinal expansion of some part of the cloud (which may be very far from thermalized) converts mainly into string tension energy, so that its expansion comes to a halt and a cold system of considerable longitudinal dimension forms before the QCD string network breaks up into pions. In such a string network picture one can indeed imagine that hadronization might be a slow process; after all, from the existence of rather narrow resonances with high spin, we know that breaking of a single string can be slow. Irrespective of whether the NA22 spike is significant or not, it may be interesting to give further thought to the cooling and hadronization of rapidly expanding clouds of QCD partons, concentrating on the formation of a string network rather than on hydrodynamical scenarios of the hadronic phase transition.

Finally, stepping down from speculation to facts, one should stress that rapidity spikes are observed rather commonly, be it broader ones than in the NA22 event, and it will be interesting to undertake statistical studies of their properties. Concepts borrowed from the theory of turbulence present themselves as natural tools for this purpose, especially the concept of intermittency. An important paper of A. Biały and R. Peschanski should be mentioned in this context$^{17}$.

6.3 Entropy ofMultiplicity Distributions

How rich the empirical properties of MDs can be was recently illustrated once more by V. Šimak et al.$^{18}$ who discovered remarkable regularities for the "entropy" $S = -\sum P_n \ln(P_n)$ of proton-(anti)proton
collisions up to the highest energies ($P_n$ is the charged particle MD). For total multiplicities $S$ turns out to grow like

$$S_t = 0.4 \gamma_m, \quad \gamma_m = \ln[(E_{CM} - 2m_p)/m_\pi]$$

and for rapidity windows $|y| < y_0$ it has the simple scaling behaviour

$$S(y_0) = 0.4\gamma_m (1 - \exp(-6.6y_0/\gamma_m))$$

Linking this property with the NB character of the MD, the authors present interesting speculations in the framework of Feynman's picture of a "gas of particles in rapidity space".

7. FURTHER REMARKS AND CONCLUSION

Looking back at the many presentations and discussions of this Workshop, what strikes me most is the large impact of the comprehensive and accurate results of recent experiments (especially HRS, NA9, NA22, UA1, UA5), and the large amount of work already done to interpret them with theoretical models and concepts. What is striking also but of course less positive is the lack of truly significant theoretical advances and predictions. It may well be that this will remain so for a while. Even when their premises remain unchanged, models like DPM, Fritiof, Parton Shower, etc. contain much uncertainty, and therefore also flexibility, at two levels:

i) the dynamics of hadronization (absence of reliable non-perturbative QCD and inability of lattice QCD to calculate MPP phenomena);

ii) the rather radical approximations needed to derive observable consequences from the model equations.

An example of radical approximation, often quoted by R. Weiner, is the common neglect in a variable phase in the wave function of the multiparticle final state, which reduces a quantum problem with interfering amplitudes to one of classical statistics (a constant phase would of course be unobservable). Contrary to what is sometimes said, this problem has not been overlooked. Almost twenty years ago, L. Michejda and others\textsuperscript{19}) pointed out that rapid variations
of the above phase with the momenta of the outgoing particles are necessary in order to reconcile via unitarity the multiparticle final-state wave function with the sharp peak of the overlap function in \((\text{momentum transfer})^2\), the latter peak being deduced from the observed elastic shadow scattering. While this was shown only in two models of the 1960's, the discrepancy is so big that the problem must be a major one for all models. To my knowledge, nobody has produced so far an ansatz for the final state multiparticle wave function satisfying the overlap function constraint.

More recently, the phase problem came up again in a major way in the QCD parton shower models, after A.H. Mueller, B.I. Ermodaev and V.S. Fadin had shown that non-leading perturbative effects in gluon production give strong destructive interferences in certain regions of phase space\(^{20}\). It was then realized that these interference effects can be approximated if one suppresses "by hand" certain phase space regions for gluon emission. The suppression is performed by imposing an angular ordering condition for branching, which can be incorporated in Monte Carlo shower models\(^{21,1}\). More recently, other interference effects implied by QCD in parton showers are being investigated quantitatively\(^{22}\).

This digression on phases and much of what was discussed before illustrate both the great complexity of multiparticle production physics and the numerous opportunities it offers for new theoretical and empirical findings. Much work is still to be done before we can hope to achieve a satisfactory synthesis and to agree on its dynamical foundation. Past experience has shown that data are only useful when they are accurate and comprehensive, and that theoretical work is only taken seriously when it confronts all relevant data. This requires an intense dialogue between experimentalists and theorists, of the type which took place so successfully during this Workshop. All participants are therefore greatly indebted to Profs. R.C. Hwa and Xie Qu-bing for their original approach and effective leadership in directing the Workshop, which made it such a profitable and pleasant experience. Our gratitude also goes to Shandong University and the many people involved in the organization for the warm hospitality we enjoyed in Jinan.
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