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PROPERTIES OF SOFT PROTON ANTIPROTON COLLISIONS

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Abstract

The properties of soft inelastic proton antiproton collisions at the CERN SPS Collider are reviewed. Among the experimental results covered are charged particle multiplicity and rapidity distributions, transverse momentum distributions and mini-jets, correlation phenomena, diffraction dissociation and searches for exotic phenomena. A brief review of some of the models proposed to describe these data is then given.

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INTRODUCTION

The primary reason for building the CERN SPS collider ("Sp $\bar{p}$ S") was to reach an energy high enough to produce the W and Z weak bosons. In this the project was triumphantly successful, as described in other contributions to this volume. However, much effort has also been devoted to the study of "soft" processes in which only low p_T particles are produced. Why? The first reason is simply that such events are there. Indeed, more than 99% of all particles produced have $p_T < 2\text{GeV}/c$. Although we have no rigorous theory of such processes (or rather we do not know how to apply QCD in this case) we should still try to understand what is going on, and to systematize the properties of this vast bulk of interactions. Furthermore, the "soft" events constitute a source of background to the other events, which seem, at present, more interesting. It is therefore necessary to have some understanding of the soft events, even if only in an empirical way. Finally we should mention the possibility of exotic effects showing up in the new energy regime opened up at the Sp $\bar{p}$ S. Indeed, there have been reports of several curious effects in cosmic ray data at these energies [1], which appear to occur with large cross-sections. It would be foolish not to search for such phenomena, which should show up in "minimum bias" data taken for the study of soft processes.

In subsequent sections we first briefly outline the Collider experiments, stressing those features important for the present topics. The experimental results will then be reviewed, mainly from an empirical point of view, particularly emphasizing the energy dependence of the phenomena studied. Of necessity the choice of data and the discussion will be selective, but we shall try to give full references to the original sources of data, where more details can be found. We shall attempt to cover most aspects of "soft" physics, with the exception of elastic scattering and the total cross-section, which are discussed elsewhere in this volume. A very brief review of the many models which have been proposed to describe various features of these data will then be given.

THE SPS COLLIDER AND THE EXPERIMENTS

The SPS Collider

The data discussed below generally come from periods when the Sp $\bar{p}$ S was operating at very low luminosity. These were, for example, the early machine development runs of the machine, without low- β . In the very first runs of the Sp $\bar{p}$ S in October–November 1981 [2] luminosities of around $10^{25}\text{cm}^{-2}\text{s}^{-1}$ were achieved, and in 1982 of typically $10^{26}\text{cm}^{-2}\text{s}^{-1}$. Such luminosities were ideally suited for triggering with a "minimum-bias" trigger designed to accept a large fraction of "soft" collisions. Most of the results presented below at $\sqrt{s} = 546\text{GeV}$ come from these early runs. In addition some special runs at different β values were taken to allow UA4 to explore elastic scattering in different t-ranges.

An important run for the study of "soft" physics was the so-called Pulsed Collider run of March – April 1985. In normal Collider running the beam energy was limited to 270 GeV (or more recently 315 GeV) because of power dissipation in the magnets. In 1982 a method was proposed [3] whereby the beam energy would be cycled repeatedly between 100 GeV and 450 GeV, enabling one to observe collisions at $\sqrt{s} = 900$ GeV with a duty factor of around 20%. This scheme was successfully implemented and a Pulsed Collider run was carried out in 1985, with luminosities of typically $10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ and beam lifetimes of a few hours. This run allowed the study of soft $\bar{p}p$ collisions at $\sqrt{s} = 900$ GeV, and incidentally also at $\sqrt{s} = 200$ GeV, giving a useful intermediate point between the old Sp $\bar{p}$ S data and data from the CERN ISR.

The experiments

There were two major experiments at the SPS Collider aimed principally at the study of "soft" processes. The UA4 experiment used "Roman pots" [4] set into the beam pipe in the far-forward region to study elastic scattering, and thereby the total cross-section. These topics are discussed elsewhere in this volume. In addition UA4 had some forward drift chambers which, combined with the central detector of UA2 allowed them to study single diffractive dissociation (see section "DIFFRACTION DISSOCIATION" below).

The other detector which has concentrated on soft inelastic processes was UA5 [5,6], shown in Figure 1. The main feature of this detector was a pair of very long streamer chambers, giving acceptance for particles out to pseudorapidity[†] = ± 5 . A detailed description of this detector and analysis techniques appears in [5]. A large share of the results discussed in this paper come from the UA5 experiment. Incidentally, the UA5 experiment also took data in a test run at the CERN ISR [7,8], meaning that it took data over an unusually wide range of c.m. energy, from 53 to 900 GeV.

Figure 1: Schematic layout of the UA5 detector.

[†] $\eta \equiv -\ln \tan \frac{\theta}{2}$, where θ is the c.m. polar angle of production)

The UA1 and UA2 experiments were primarily designed for the study of vector bosons and high p_T phenomena. However, especially in the early days of Collider running when the luminosity was low, these experiments made valuable measurements on soft processes. UA1 is a general purpose detector, and thus capable of many studies in the soft physics area, but once the luminosity was high enough their main interests were obviously in other areas. In addition, UA1 took data during the Pulsed Collider run. UA2 is perhaps more specialized towards W, Z and jet physics, but during their first runs they replaced part of their central calorimeter by a "wedge" spectrometer, to observe particle production at 90° in soft collisions.

Triggering

Before discussing the results from the Sp $\bar{p}$ S a few points should be made concerning triggering, since the problems are somewhat different from lower energy experiments. The discussion will be centred on the UA5 detector (Figure 1), but the principles are the same for the others. The normal trigger used is called a "two-arm" trigger, requiring hits in the trigger counters at both ends of the detector in coincidence with a beam crossing. UA1 and UA2 used a similar trigger. This is often referred to as a "minimum-bias" trigger, but this term can be misleading. The two-arm trigger accepts most inelastic events, except that it has a low efficiency for single-diffractive (SD) events, which are normally highly asymmetric. The recoil proton or $\bar{p}$ in a diffractive event essentially always passes inside the beam pipe. Therefore to capture SD events a single-arm trigger must be employed, demanding hits in only one set of trigger counters. Such a trigger was very susceptible to background, and was only enabled by UA5 for a few runs, most successfully in the Pulsed Collider run. UA4 were able sometimes to detect the recoil $p/\bar{p}$ in SD events in their pots.

The typical relationship between event classes and triggers is outlined in Figure 2. The precise numerical values vary from experiment to experiment, and from energy to energy. To a first approximation, the two-arm trigger which is normally employed corresponds to non - single-diffractive (NSD) events, and most of the results from the Sp $\bar{p}$ S correspond to NSD events. In contrast, the lower energy data with which we wish to compare generally correspond to the full inelastic cross-section. They may in some cases be converted to NSD data using published results on diffraction dissociation. In the Sp $\bar{p}$ S data we only have full inelastic (sometimes called "inclusive") data for cases where it was possible to combine single-arm and two-arm triggers. This must be borne in mind when comparing data at different energies.

CHARGED PARTICLE MULTIPLICITIES

Average Multiplicity

There are extensive data at lower energies on charged particle multiplicity distributions and thus on average multiplicities. The bulk of these data come from bubble chamber experiments, where this is one of the most straightforward measurements to make. The experimental problems are somewhat different at a colliding beam machine, where even the best detectors have limited acceptance. At the Sp $\bar{p}$ S the UA5 detector has the greatest acceptance for charged tracks. The UA5 correction procedures are described in detail elsewhere [5,9], and the data are given in [5,9,10,11].

The data for $\langle n_{ch} \rangle$ versus $\sqrt{s}$ in NSD events are shown in Figure 3. Two fits to the data are also shown, a quadratic in $\ln s$ (solid curve):

$$\langle n_{ch} \rangle_{NSD} = 2.7 - 0.03 \ln s + 0.176 \ln^2 s \quad : \quad \chi^2/d.f. = 17/9 \quad (1)$$

and a power law (dashed curve):

Figure 2: Relationship between event categories and trigger types. The numerical values given relate to the UA5 experiment at $\sqrt{s} = 900\text{GeV}$.

$$\langle n_{ch} \rangle_{NSD} = -7.0 + 7.2s^{0.127} \quad : \chi^2/df. = 11/7 \quad (2)$$

The $\ln^2 s$ fit, which gave an entirely adequate description of the data up to ISR energies, is still a reasonable fit, though there is maybe a hint that the data are rising above this fitted curve. Indeed, the power law fit gives a slightly better χ^2 , and fits the higher data points better, but the difference is clearly marginal considering the errors on the Sp̄pS data. Similar conclusions follow for the full inelastic $\langle n_{ch} \rangle$ (not shown). Further discussion of average multiplicities of various particle species appears in [5].

Multiplicity Distributions and KNO scaling

The Sp̄pS data from UA5 and UA1 have revived interest in the subject of KNO scaling. The original KNO hypothesis [12]

$$\langle n \rangle \sigma_n / \sum_0^\infty \sigma_n \xrightarrow{s \rightarrow \infty} \psi(z) ; \text{ where } z = n / \langle n \rangle \quad (3)$$

was based on Feynman scaling [13], which has long been known to be violated in the central region [14]. Nonetheless, KNO scaling, which implies that the *shape* of multiplicity distributions should *asymptotically* become energy independent, has proved a useful framework for the discussion of the energy dependence of multiplicity distributions. Data up to ISR energies had shown that the full inelastic distributions did not scale [14]. One reason for this might be the mixing of SD and NSD processes, with different energy dependences, and indeed the NSD data up to $\sqrt{s} = 63\text{GeV}$ were compatible with KNO scaling [15]. However, it should be pointed out that there are fewer data available for NSD than for full inelastic, and that the different experiments use different techniques for the separation of the SD events.

The early UA5 data from the Sp̄pS [16] showed that KNO scaling between FNAL and Sp̄pS energies was excluded for NSD events. Later data from UA5, by which time ISR data were available

Figure 3: Average charged multiplicity in NSD events vs. $\sqrt{s}$. The curves are described in the text.

also, confirmed the effect [17]. This is shown by the data of Figure 4, which compares the UA5 546 GeV data in KNO-scaled form with lower energy data. The UA5 data clearly follow a broader distribution.

The effect is confirmed by the 200 and 900 GeV NSD data [10]. For example, Figure 5 shows the C-moments[†] as a function of $\sqrt{s}$ up to 900 GeV, and also the fractions of events having $z > 1.5$, 2 or 2.5. The C-moments and the fractions of high multiplicity events are rising throughout the Sp $\bar{p}$ S energy range, and the effect is most pronounced for the highest multiplicities.

For the full inelastic data, KNO scaling was already ruled out by the ISR data [14]. For example Figure 6 shows a "Wróblewski" plot, of $D_2^{\dagger\dagger}$ against $\langle n \rangle$. The data up to ISR energies lie nicely on straight lines. However, unlike the NSD case, the inelastic data cross the $\langle n \rangle$ -axis not at the origin but at $\langle n \rangle = \alpha$, where α is close to 1. This corresponds to KNO scaling in the variable $(n - \alpha)$ rather than n , and may be regarded as "asymptotic KNO scaling" as n becomes large [18,5]. However, the Sp $\bar{p}$ S data from UA5 show clear deviations from even this behaviour, and thus seem to show no sign of asymptotic scaling. Another extension of KNO scaling, "KNO-G scaling" [19], is close to this $(n - \alpha)$ scaling behaviour, and is equally incompatible with the Sp $\bar{p}$ S data. A recent analysis, in the context of a statistical model, has shown that the data can only be accommodated in such a modified KNO framework if the parameter α is allowed to vary with $\sqrt{s}$ [20].

[†] The C-moments, defined by $C_q = \langle n^q \rangle / \langle n \rangle^q$, should be independent of c.m. energy in the case of ideal KNO scaling.

^{††} The D-moments are defined by $D_q = \langle (n - \langle n \rangle)^q \rangle^{1/q}$, and D_q should be proportional to $\langle n \rangle$ in the case of perfect KNO scaling. Only D_2 is shown in Figure 6, but the higher moments show the same behaviour.

Figure 4: Test of KNO-scaling for NSD multiplicity distributions. Note that the UA5 546GeV distribution is broader.

However, there were indications from the early UA1 data [21,22] that KNO scaling held reasonably well in the central region, $|\eta| < 1.5$, and this appeared to be confirmed by the UA5 data [17], though there were some doubts whether the trigger conditions were strictly comparable between the ISR and Sp $\bar{p}$ S data. Recently, UA5 has made a systematic study of multiplicity distributions at $\sqrt{s} = 200, 546$ and 900GeV , for various rapidity regions, $|\eta| < \eta_c$ [23,24,11]. In Figure 7 the energy dependence of some C_2 for various values of η_c is shown. We see that the value of C_2 grows with energy for all values of η_c , except for $\eta_c \leq 0.5$, where C_2 is rather constant, and maybe even starts to fall with $\sqrt{s}$. The higher C-moments show similar behaviour, though possibly flattening out at slightly lower values of η_c . These data have passed through the same correction procedures at each energy, and are therefore free of many of the uncertainties which affected the earlier comparisons. This suggests that the earlier observation of approximate scaling for $\eta_c = 1.5$ may have been somewhat fortuitous.

Negative Binomial Description of Multiplicity distributions

Recently UA5 have analyzed their multiplicity data in a different way, which gives an alternative view to KNO scaling. They have observed [25,10] that the NSD multiplicity distributions at all energies may be very well described by the negative binomial distribution:

$$P(n; \langle n \rangle, k) = \left[\begin{matrix} n+k-1 \\ k-1 \end{matrix} \right] \frac{(\langle n \rangle / k)^n}{(1 + \langle n \rangle / k)^{n+k}} \quad (4)$$

This distribution had previously been proposed for such an application by several authors (e.g. refs. [26,27,28]). The UA5 fits are very good, though of course one cannot exclude the possibility that the

Figure 5: (a) C-moments for NSD data vs. $\sqrt{s}$. (b) fraction of events having multiplicity greater than some multiple of $\langle n \rangle$, vs. $\sqrt{s}$.

Figure 6: Plots of D_2 versus $\langle n \rangle$ for inelastic and NSD data.

Figure 7: C_2 vs. $\sqrt{s}$ for various values of η_c

fits are only approximate; indeed, UA5 suggest that a negative binomial distribution for underlying clusters might fit equally well given the statistical errors. There is also some hint in the latest UA5 data that the quality of the fit may be less good for the full pseudorapidity range at the highest SpP S energy, $\sqrt{s} = 900\text{GeV}$ [11].

Two parameters are required to specify this distribution, $\langle n \rangle$ and k , and it turns out that both vary smoothly with $\sqrt{s}$. Fits to $\langle n \rangle$ were discussed in section "Average Multiplicity" above, whilst k may be very well fitted by the form

$$k^{-1} = -0.104 + 0.058 \ln \sqrt{s} \quad ; \quad \sqrt{s} \text{ in GeV} \quad (5)$$

This leads one to a simple way of parametrizing multiplicity distributions at all energies, using the fits to $\langle n \rangle$ and k instead of KNO scaling. Indeed, this idea has been applied to "predict" multiplicity distributions at the SSC, $\sqrt{s} = 40\text{TeV}$ [25,29].

It is of interest to compare this way of describing multiplicity distributions with the KNO scaling scheme. First we note that for large $\langle n \rangle$ the negative binomial takes the form:

$$\langle n \rangle P(n; k) \approx [k^k / \Gamma(k)] z^k e^{-kz} \quad ; \quad \text{where } z = n / \langle n \rangle \quad (6)$$

This would correspond to KNO scaling if k were to approach a constant value. However up to $\sqrt{s} = 900\text{GeV}$ there is no sign of this [10], see also Figure 8.

What then of the KNO scaling seen up to ISR energies? In the negative binomial picture this scaling would appear to be fortuitous. We may see this by noting that the moment γ_2 is given by:

$$\gamma_2 \equiv C_2 - 1 = 1 / \langle n \rangle + 1/k. \quad (7)$$

The data of Figure 8 show that $1/\langle n \rangle$ falls with $\sqrt{s}$, while $1/k$ rises, and over the FNAL/ISR energy region they add to give a broad minimum. Similar formulae apply to the higher C-moments, and thus approximate KNO scaling ensues. Since the parameters $\langle n \rangle$ and k have smooth and simple energy dependence one might infer that the KNO scaling up to ISR energies was accidental. Certainly the data of Figure 5 do not conclusively establish the existence of scaling; arguably the FNAL/ISR data have neither a long enough lever arm in energy nor sufficient precision.

Figure 8: The smooth variation of $\langle n \rangle^{-1}$ and k^{-1} with $\sqrt{s}$. Thus approximate KNO scaling appears for $10 \leq \sqrt{s} \leq 100 \text{ GeV}$.

Another point of view is that the KNO scaling up to $\sqrt{s} = 63 \text{ GeV}$ is significant, and that the scaling violations at the Sp̄pS reflect the onset of new physics. The likeliest candidate for such a new component is a rising hard or semi-hard scattering component. For example the authors of ref [30] have argued that this is a consistent view of the data. Indeed, there is little doubt that such processes are becoming more important, since UA1 have evidence for such a contribution (see section "Mini-jets" below). This topic will be discussed further under "Microscopic models" below. It is not clear, however, how to reconcile such a picture with the smooth behaviour of the negative binomial parameters from FNAL/ISR energies (where jets are unimportant) to the highest Sp̄pS energy.

We should also note that the negative binomial distribution gives excellent fits to multiplicity distributions in limited rapidity intervals [31,11], see Figure 9. The parameter k rises approximately linearly with the size of the rapidity interval, approaching a value ≈ 1.5 for very small intervals. As $\sqrt{s}$ increases, then k rises for all rapidity intervals (in contrast to C_2 , for which the trend is reversed in small intervals — this is because C_2 includes dependence on $\langle n \rangle$ as well as k). Note that a Poisson distribution is a special case of a negative binomial with $k = \infty$. Thus the multiplicity distributions are relatively broader, and deviate increasingly from a Poisson form, as the rapidity interval is made smaller. Further discussion of the negative binomial distribution in the context of models appears in "Statistical models" below.

Figure 9: Multiplicity distributions for various values of η_c at $\sqrt{s} = 546 \text{ GeV}$. The curves show the quality of the negative binomial fits.

PSEUDORAPIDITY DISTRIBUTIONS

Measurements of charged particle pseudorapidity distributions and particle multiplicities near $\eta = 0$ were among the first observations made at the Sp $\bar{p}$ S [32,33,21,22]. The latest and most precise data come from UA5 [34], who have analyzed data at $\sqrt{s} = 53, 200, 546$ and 900 GeV with essentially the same techniques. These data should therefore have small relative systematic errors, and be particularly suitable for study of energy dependences. Both NSD and inelastic data have been presented, and the general conclusions drawn from both are similar.

In Figure 10 the UA5 NSD data are shown. We see that both the height and width of the pseudorapidity distributions increase with $\sqrt{s}$. The charged particle density at $\eta = 0$, $\rho(0)$, is plotted against $\sqrt{s}$ in Figure 11. The growth of $\rho(0)$ with $\sqrt{s}$ confirms the violation of Feynman scaling seen at the ISR [14]. Good fits to the energy dependence of $\rho(0)$ (for the inelastic data) are given by the forms:

$$\rho(0) = 0.01 + 0.22 \ln s \quad ; \quad \chi^2/d.f. = 6.0/7 \quad (8)$$

or

$$\rho(0) = 0.74 s^{0.105} \quad ; \quad \chi^2/d.f. = 4.8/7 \quad (9)$$

The χ^2 -values clearly do not allow one to choose between these forms.

The question of Feynman scaling in the beam fragmentation region is however not settled. In an attempt to look at this question the UA5 inelastic data for $\rho(\eta)$ have been plotted (Figure 12) against the variable η_{beam}

Figure 10: Charged particle NSD η distributions from UA5.

Figure 11: Energy dependence of $\rho(0)$ for both NSD and inelastic data. The fits are described in the text.

$$\eta_{beam} \equiv \eta - Y_{beam}; \text{ where } Y_{beam} = \ln(\sqrt{s}/m_p) \quad (10)$$

which approximates to the particle rapidity in the beam's rest frame. We see that the data from $\sqrt{s} = 53$ to 900GeV roughly scale (to $\pm 10\%$) in the region $|\eta_{beam}| < 2.5$.[†] One simple way to describe the data in the beam fragmentation frame would be by a rise along an energy-independent curve until the (energy-dependent) plateau level $\rho(0)$ is reached, where the distribution flattens out. On closer inspection, however, there is perhaps a hint that the higher energy data fall off slightly more steeply than the lower energy points, suggesting some scaling violations. The data do not seem to be quite precise enough, or the rapidity range not quite wide enough, to resolve this question. Maybe the UA7 experiment, who have just presented their first results on photon production in the region $5 < |\eta| < 7$ [35] using very forward calorimetry will be able to shed further light on this question.

Figure 12: Test of fragmentation region scaling in the UA5 inelastic data.

Some interpretations of cosmic ray data have led to the suggestion of significant scaling violations in the beam fragmentation region [36,37]. Wdowczyk and Wolfendale have put forward [38,39] an elegant way to link such scaling violations to the well-established violations at $\eta = 0$. Their idea is simply to replace the Feynman variable x_F by $x' = x_F(s/s_0)^k$. They also take account of a (hypothesized) decrease in the inelasticity^{††} with $\sqrt{s}$. The UA5 data have been shown to be compatible with the Wdowczyk-Wolfendale framework, but only if the inelasticity falls strongly with $\sqrt{s}$, dropping by around 50% between 53 and 900GeV . There is no direct evidence on this point, but such a strong fall seems somewhat implausible.

[†] For a typical particle p_T of $0.4\text{GeV}/c$ a value $\eta_{beam} > -2.5$ corresponds roughly to Feynman- x ($x_F = 2p_T/\sqrt{s}$) > 0.05 . One should note that the UA5 acceptance, $|\eta| < 5$, corresponds roughly to $|x_F| < 0.3(0.065)$ at $\sqrt{s} = 200(900)\text{GeV}$. Thus the UA5 data do not really probe the high- $|x_F|$ part of the distribution.

^{††} The inelasticity, k , is the fraction of the c.m. energy *not* carried off by leading particles.

UA5 have also presented data on charged particle pseudorapidity distributions as a function of charged multiplicity. The data for NSD events at $\sqrt{s} = 200$ and 900 GeV are shown in Figure 13. We note that the growth of particle density with multiplicity is greatest in the central region. At fixed multiplicity, as $\sqrt{s}$ increases, the distribution becomes broader and the plateau lower. Both these effects may be expected to have a mainly kinematic origin [54]. In Figure 14 we show the dependence of $\rho_n(0)$ on n_{ch} . The rise of $\rho_n(0)$ with n is faster than linear, reflecting the narrowing of the distributions with n . The rise is greater at lower $\sqrt{s}$, but the ratio between the values of $\rho_n(0)$ at two different energies for the same value of n seems to be independent of n . If the central density scaled to the overall average ($\rho_n(0)/\rho(0)$) is plotted against the KNO variable ($z = n / \langle n \rangle$) a striking energy independent scaling behaviour is seen (Figure 14).

Figure 13: Pseudorapidity distributions in different ranges of n_{ch}

TRANSVERSE MOMENTUM

Single particle distributions and $\langle p_T \rangle$

In order to put together a complete picture of this topic at the Sp $\bar{p}$ S we need to use data from several of the experiments:

- UA1 have made measurements of charged particle p_T spectra using their central detector, both at 546 GeV [40] (in the region $|y| < 2.5$, and $0.3 \text{ GeV}/c < p_T < 10 \text{ GeV}/c$) and in the Pulsed Collider run from 200 to 900 GeV [41] (reaching lower values of p_T down to $0.15 \text{ GeV}/c$).
- UA2 used their wedge spectrometer to measure charged particle spectra near $\eta = 0$ in the range $0.4 \text{ GeV}/c < p_T < 2 \text{ GeV}/c$ [42]. They were able to use time-of-flight measurements to separate pions, kaons and protons over various smaller ranges of p_T .

Figure 14: (a) Central density, $\rho_n(0)$, vs. n at 200, 546 and 900 GeV. (b) Ratios of $\rho_n(0)$ between pairs of energies. (c) Scaling behaviour when $\rho_n(0)/\rho(0)$ is plotted against $n/\langle n \rangle$. The inset shows the points nearest the origin on an expanded (logarithmic) scale.

- Despite having no magnetic field, the UA5 collaboration was able to use various kinematic constraints to identify and measure p_T spectra for several strange particles, namely $K^\pm$ and K_s^0 [43,44,45,5,46], Λ^0 [43,5,46] and Ξ^- [47,5,46]. These data refer to the central rapidity region ($|y| < 2$ to 3.5 typically) and the $K^\pm/K_s^0$ data cover the full p_T -range down to zero, while the Λ^0 and Ξ^- data cover the regions $p_T > 0.2$ and $0.6 \text{ GeV}/c$ respectively. UA5 also have some data on photon spectra [48,49,5] using their calorimeter, and indirectly on charged particles using multiple scattering measurements [8,5].

The UA1 charged particle data are the most precise, and cover a wide range of p_T ; they are shown in Figure 15. The data diverge markedly from the exponential behaviour which was often observed at low energies. UA1 have obtained excellent fits to their data using the form:

$$E \frac{d^3\sigma}{dp^3} = \frac{A p_0^n}{(p_0 + p_T)^n} \quad (11)$$

and have used such fits to extrapolate to $p_T=0$, and thus estimate $\langle p_T \rangle$. It has however been suggested [50] that near $p_T=0$ an exponential form like

$$E \frac{d^3\sigma}{dp^3} = B e^{-bm_T} \quad ; \text{ where } m_T = \sqrt{(p_T^2 + m^2)} \quad (12)$$

should be expected. The UA5 data on kaons (shown in Figure 16, and compared with the UA2 data, which agree well) have therefore been fitted with a hybrid form, a power law at high p_T and an exponential in m_T at low p_T †

† The two functions and their first derivatives were constrained to be continuous at the crossover point, chosen to be $p_T=0.4 \text{ GeV}/c$.

Figure 15: p_T -distribution for charged particles from UA1 at 546 GeV.

Figure 16: p_T -distribution for kaons from UA5 and UA2 at 546 GeV.

There are therefore some uncertainties in estimating $\langle p_T \rangle$, but trends with $\sqrt{s}$ should be correctly measured where a consistent fitting procedure was used. In Figure 17 we show the dependence of $\langle p_T \rangle$ on $\sqrt{s}$ for various particle species, using the Sp̄pS data and a compilation of data up to ISR energies [51]. The data up to the ISR showed a very slow rise of $\langle p_T \rangle$ with $\sqrt{s}$. The UA1 charged particle data show a much stronger rate of increase over the Sp̄pS energy range, from $\approx 0.39\text{GeV}/c$ at $\sqrt{s}=200\text{GeV}$ to $\approx 0.44\text{GeV}/c$ at 900GeV . The kaon and baryon data have much larger errors, but they clearly confirm the effect, and indeed show a more dramatic rise.[†] The most natural explanation for this increased growth is the onset of significant jet production over the Sp̄pS energy region. The greater increase for heavy particles is presumably a simple mass effect, since the effects of resonance decays (and jet fragmentation if appropriate) tend to push the pions down to lower p_T . The heavy particles carry off a larger fraction of the momentum of their parent (whether it be a resonance or a parton) for kinematic reasons. Thus the strong rise in $\langle p_T \rangle$ for kaons and baryons may be expected to reflect the changes in the underlying dynamics more directly than the data for all charged particles, which are dominated by pions.

Figure 17: Energy dependence of $\langle p_T \rangle$ for various particle species.

UA1 have also noted a strong correlation between $\langle p_T \rangle$ and multiplicity (Figure 18). This effect had not been seen at the ISR, although a much weaker effect has now been observed [52]. The UA5 kaon and photon data [48,5,44] show a similar effect, though the errors are much greater. One of the first interpretations of this effect [53,50] was in terms of quark-gluon plasma formation, the flattening off in the rise of $\langle p_T \rangle$ representing an increase of entropy with no associated increase of temperature, i.e. a phase transition. It now appears (section "Mini-jets" below) that the correlation is connected with jet production, though a full quantitative understanding is still awaited.

[†] The UA5 estimate of $\langle p_T \rangle$ for Ξ^- production at 546GeV , $1.1 \pm 0.3\text{GeV}/c$, is particularly high, though the statistical error is large; one should also note that UA5 have poor acceptance for Ξ^- at low p_T . The preliminary data at 200 and 900GeV [46] already hint that this was an upward fluctuation.

Figure 18: Correlation of $\langle p_T \rangle$ with $dn/d\eta$ for UA1 data at 546 GeV.

"Mini-jets"

A recent study which may be of importance in accounting for some of the features of "soft" collisions has been UA1's observations [41] of copious jet production in "minimum-bias" events, so-called "mini-jets". In essence UA1 took their standard jet-finding algorithm which they use for high- p_T events and ran it on "minimum-bias" triggers. They were able to convince themselves on a number of grounds that the "jets" found by this procedure were reasonably reliable down to $E_T \approx 5$ GeV. They find that a large fraction of "minimum-bias" events contain such "jets", rising from $\approx 6\%$ at $\sqrt{s} = 200$ GeV to $\approx 17\%$ at $\sqrt{s} = 900$ GeV. The reliability of this jet identification at such low energies is not entirely accepted yet,[†] but even if only a fraction of these events really come from "semi-hard" scattering their influence on what we normally refer to as "soft" physics may be important.

For example, the abrupt increase in $\langle p_T \rangle$ with $\sqrt{s}$ (Figure 17) could well be accounted for by the onset of significant jet production above ISR energies. Furthermore, UA1 have separated their events into those with and without jets. The jet events have average multiplicity roughly double that of no-jet events. Thus the average p_T of high multiplicity events should be greater than low multiplicity events, as observed (Figure 18). Indeed, UA1 see that $\langle p_T \rangle$ for jet events is roughly constant at ≈ 0.5 GeV/c, while the non-jet events still show some correlation between $\langle p_T \rangle$ and multiplicity (maybe owing to non-identified jets or jets below 5 GeV).

[†] For example, the UA5 collaboration have found [54] that their cluster Monte Carlo produces "mini-jets" at something like half to two-thirds of the rate seen by UA1, and with rather similar properties. In essence a cluster of $E_T = 5$ GeV looks very much like a jet of the same E_T . This does not by any means imply that the UA1 interpretation is incorrect, but it does indicate that other interpretations might be possible, and thus that caution is called for.

Since the jet component of the cross-section is growing with $\sqrt{s}$, and the jet events are of higher than average multiplicity, we may envisage some connection with the KNO scaling violations observed at the Sp̄pS, as mentioned above under section "Multiplicity Distributions and KNO scaling". UA1 have suggested that the jet and no-jet samples separately show KNO scaling between 200 and 900 GeV (in $|\eta| < 2.5$), though it is not clear whether the scaling seen is in fact any better than that for the combined data sample.

Finally, UA1 have suggested that the rise in the cross-section for events containing jets roughly equals the absolute rise in σ_{tot} with $\sqrt{s}$, and thus they imply that in some sense the rise of σ_{tot} is due to the hard-scattering component. In fact the rise of the jet cross-section may be rather too sharp. However, in view of the inevitable uncertainties in defining jets of such low E_T as 5 GeV, we should probably regard all this discussion as only semi-quantitative, and not be too concerned by this. In summary, even if the UA1 data may be questioned at the detailed quantitative level, they clearly indicate a mechanism which can affect many of the changing trends seen in the soft physics data above.

PARTICLE COMPOSITION

By using many pieces of data from the different collider experiments (charged particles, K, Λ , Ξ , γ from UA5; K, p from UA2) the UA5 collaboration has attempted to piece together a picture of the composition of a typical "soft" event at the Sp̄pS [16,5]. The measurements were made in various different kinematic regions, and have been extrapolated to the full p_T range and rapidity range for comparison, as described in ref [5]. Various other plausible assumptions were also made, as detailed in Table 1, where the results are summarized.

The multiplicity dependence of the particle composition is not too well known. The UA5 photon data show the number of photons to be linearly related to n_{ch} [55]. A similar result seems to hold for the kaons [43,44], though the statistics are meagre. Also UA5 have observed that the average multiplicity of events containing a Ξ^- is as expected assuming a multiplicity-independent $\Xi/\text{charged}$ ratio. We can thus conclude that there is no evidence requiring any variation of the particle composition with multiplicity.

We note that the data show a substantial excess of photons compared to $\pi^+ + \pi^-$ (though the errors are large; data at 200 and 900 GeV will be of interest, but are not available at the time of writing). Naïvely one would expect that the yields of π^+ , π^- and π^0 would be equal (from isospin symmetry), and it has been suggested therefore that substantial production of η -mesons could be indicated [55]. An η/π^0 ratio of $30 \pm 10\%$ would account for the observations.

In Figure 19 we see the variation of the $K^\pm/\pi^\pm$ ratio with $\sqrt{s}$; the rise above kaon production threshold is flattening out, though the ratio seems to be still rising. Also in Figure 19 we show the K/π ratio as a function of p_T for data at $\sqrt{s} = 53$ GeV and 546 GeV. The same rise with p_T is seen at both energies, suggesting a connection between the rise of $\langle p_T \rangle$ with $\sqrt{s}$ and the rise of the K/π ratio [44]. If we take η production to account for the photon excess we deduce that of the "stable" particles (i.e. after strong decays) produced at $\sqrt{s} = 546$ GeV $\approx 10\%$ are kaons, and $\approx 8\%$ are baryons or antibaryons. For comparison, a similar analysis applied to ISR data yields 9% and 5% respectively [16]. Thus baryon production in particular seems to have increased with $\sqrt{s}$. This appears to be confirmed internally by the Sp̄pS data; between 200 and 900 GeV baryon production seems to have increased by a factor ~ 2 [46,49], whilst $\langle n_{\text{ch}} \rangle$ has risen by only around 50%.

The K/π ratio has been used to derive the "strangeness suppression factor", λ , which is the ratio of the number of $s\bar{s}$ quark pairs produced to the number of $u\bar{u}$ (or $d\bar{d}$) pairs. This factor is used, for example, in fragmentation models such as the Lund string model. It has recently been important in

Table 1: Particle composition of a typical event at $\sqrt{s} = 546\text{GeV}$.

Particle Type	$\langle n \rangle$	Source of estimate.
All charged	29.4 ± 0.3	UA5 [5]
$K^0 + \bar{K}^0$	2.24 ± 0.16	{UA5 [44]
$K^+ + K^-$	2.24 ± 0.16	{charged + neutral assumed equal
$p + \bar{p}^{(\dagger)}$	1.45 ± 0.15	UA2 [42], exapolated by UA5[5]
$n + \bar{n}^{(\dagger\dagger)}$	1.45 ± 0.15	assumed equal to $p + \bar{p}^{(\dagger)}$
$\Lambda + \bar{\Lambda} + \Sigma^0 + \bar{\Sigma}^0$	0.53 ± 0.11	UA5 [5]
$\Sigma^+ + \Sigma^- + \bar{\Sigma}^+ + \bar{\Sigma}^-$	0.27 ± 0.06	assume $\Lambda = (\Sigma^+ + \Sigma^0 + \Sigma^-)$; $\Sigma^+ = \Sigma^0 = \Sigma^-$
$\Xi^- + \bar{\Xi}^+$	0.10 ± 0.03	UA5 [47]
$\Xi^0 + \bar{\Xi}^0$	0.10 ± 0.03	assumed equal to $\Xi^- + \bar{\Xi}^+$
γ	33 ± 3	UA5 [55]
$e^+ + e^-$	0.41 ± 0.04	Dalitz pairs, based on γ
$\pi^+ + \pi^-$	23.9 ± 0.4	Subtract other sources from n_{ch}

(†) Note that leading baryons, one baryon and one antibaryon per event, are not included here. We assume one leading charged baryon in computing the $\pi^+ + \pi^-$ yield.

(††) There are estimates of the $\bar{n}$ yield from the UA5 calorimeter[48,49] which are consistent with this assumption.

Figure 19: (a) $K^\pm/\pi^\pm$ ratio vs $\sqrt{s}$. (b) $K^\pm/\pi^\pm$ ratio vs p_T

interpreting UA1's results on $B^0 - \bar{B}^0$ mixing, since it determines the relative numbers of B^0 , and B^0_s mesons produced. However, the derivation of the λ parameter from the measured K/π ratio is not unambiguous, since one needs to exclude the $q\bar{q}$ pairs formed in resonance decay from the calculation. Analyses of data below Sp $\bar{p}$ S energies gave conflicting conclusions: an analysis by Malhotra and Orava [56], based on a statistical quark model of Anisovich and Kobrinski [57], has suggested an energy independent value for λ around 0.29, while the 'quark counting' method proposed by Wróblewski [58] favours a gentle rise with c.m. energy. At Sp $\bar{p}$ S energies the two methods give consistent results within errors [44,67], and are compatible with either a constant or a slowly rising value of λ . The values estimated at the Sp $\bar{p}$ S are 0.29 ± 0.05 , 0.30 ± 0.03 and 0.33 ± 0.03 at $\sqrt{s} = 200, 546$ and 900 GeV respectively [44,45].

The Λ/p ratio seems to be roughly 1/3 right up to $\sqrt{s} = 900 \text{ GeV}$ [46], about the same as at the ISR and lower energies. In contrast the Ξ/Λ ratio has grown strongly, judging from the UA5 546 GeV data, though the errors are large (and asymmetric) [47]. It has recently been suggested that copious Ξ production would be a good signature for quark-gluon plasma production [59]. However, in view of the limited statistics on which the UA5 Ξ data are based it might be prudent to await the equivalent data at $\sqrt{s} = 200$ and 900 GeV before drawing conclusions. The first preliminary indications at 900 GeV [46] indeed hint that the 546 GeV measurement could be an upward fluctuation, though the Ξ/Λ ratio is probably still rising.

CORRELATIONS

In the present short review it is impossible to give a comprehensive review of this complicated subject. The latest UA5 data are well summarized in a recent paper [60], to which the reader is referred for details. Earlier results were presented in refs [61,62]. There are three main methods which have been used to investigate correlations: two-particle correlations, forward-backward multiplicity correlations and rapidity gap correlations. We have to try to make a coherent interpretation of all these data. It turns out that a cluster model together with the observed behaviour of multiplicity distributions is able to give a reasonable description of the data.

Two-particle correlations

These studies have followed generally similar lines to ISR and bubble chamber experiments. Starting from the single- and two-particle densities in rapidity, $\rho^I(\eta)$ and $\rho^{II}(\eta)$, one defines the two particle correlation function:

$$C(\eta_1, \eta_2) = \rho^{II}(\eta_1, \eta_2) - \rho^I(\eta_1)\rho^I(\eta_2). \quad (13)$$

Analogously one can define $C_n(\eta_1, \eta_2)$ at fixed multiplicity n . It is helpful to note that the overall correlation function can be expressed in terms of the C_n 's as follows:

$$C(\eta_1, \eta_2) = C_S(\eta_1, \eta_2) + C_L(\eta_1, \eta_2), \quad (14)$$

where

$$C_S(\eta_1, \eta_2) = \sum_n \frac{\sigma_n}{\sum_n \sigma_n} C_n(\eta_1, \eta_2); \quad (15)$$

$$C_L(\eta_1, \eta_2) = \sum_n \frac{\sigma_n}{\sum_n \sigma_n} (\rho^I(\eta_1) - \rho_n^I(\eta_1))(\rho^I(\eta_2) - \rho_n^I(\eta_2)). \quad (16)$$

These correlation functions are shown for the UA5 data in Figure 20. The C_S term has a narrow peak around $\eta_1 = \eta_2$, and reflects short-range correlations at fixed multiplicity, n . The C_L term arises because of the mixing of events of different n , which have different single particle densities, ρ_n^I . This term has a broad distribution in $\eta_1 - \eta_2$, and is thus often referred to as a "long-range" component, though the expression "mixing term" might be more appropriate. Clearly C_S is the interesting term which tells us about the effect of correlations on the two-particle densities ρ_n^{II} . One sees from Figure 20 that the change with $\sqrt{s}$ is mainly in the mixing term C_L , while the short-range term changes rather little.

Figure 20: Correlation functions C , C_L and C_S for UA5 data at $\sqrt{s} = 200, 546$ and 900 GeV .

UA5 have extracted the C_n correlation functions from data, and interpreted them in a cluster model. In such a model the correlation function should be fitted by a Gaussian superimposed on some (predicted) background. The width of the Gaussian peak gives the decay width, δ_n , of the clusters at multiplicity n , while the height of the Gaussian may be related to the cluster decay multiplicity, specifically to $\langle \kappa(\kappa - 1) \rangle / \langle \kappa \rangle$, where κ is the number of charged particles into which a cluster decays. In Figure 21 we show the values of δ_n and $\langle \kappa(\kappa - 1) \rangle / \langle \kappa \rangle$ versus $z (= n / \langle n \rangle)$ for the UA5 data at 200, 546 and 900 GeV , with ISR data [63,64] for comparison. We see that the cluster width δ_n shows little multiplicity dependence, maybe a gentle fall, and also little dependence on $\sqrt{s}$, maybe a slight rise. The decay multiplicity moment $\langle \kappa(\kappa - 1) \rangle / \langle \kappa \rangle$ again varies only weakly with multiplicity (gently rising in the UA5 data), but its energy dependence is far from clear. The UA5 data, all analysed identically, show essentially no dependence on $\sqrt{s}$, but lie above the ISR data. However, the two ISR experiments clearly disagree with each other, so maybe the internal agreement of the Sp $\bar{p}$ S data is the significant observation here. The UA5 data are shown [60] to be consistent with production of clusters having the same properties at all values of $\sqrt{s}$ and n . The average cluster multiplicity, $\langle \kappa \rangle_0$,[†] is approximately 1.6 for a Poisson decay multiplicity distribution. The distribution of κ is of course unknown, but a Poisson form is not unreasonable, though a different assumption would

[†] The angle brackets with subscript ₀ ($\langle \kappa \rangle_0$) signify that clusters decaying into only neutral particles are included in the mean. If the subscript ₀ is omitted then $\kappa = 0$ is excluded from the moments. For example a Poisson distribution with $\langle \kappa \rangle_0 \approx 1.6$ will have $\langle \kappa \rangle \approx 2.0$.

clearly lead to a different estimate of $\langle \kappa \rangle$. The distribution of κ will influence the form of the $\langle \kappa(\kappa-1) \rangle / \langle \kappa \rangle$ vs. z curve (Figure 21). For example, in ref [60] it is shown that a Poisson form fits well (under the assumptions that the overall multiplicity distribution is negative binomial, and that size of clusters is independent of the number of clusters formed), though other possibilities cannot be excluded.

Figure 21: (a) $\langle \kappa(\kappa-1) \rangle / \langle \kappa \rangle$ vs z . (b) δ_n vs z

Forward-backward multiplicity correlations

The idea here (following ref [65]) is to study correlations between the charged multiplicities in two symmetric forward and backward rapidity intervals. If the multiplicities are n_F and n_B respectively then the correlation coefficient, b , is defined by:

$$b = \frac{\text{cov}(n_F, n_B)}{\sqrt{\text{var}(n_F) \text{var}(n_B)}} \quad (17)$$

In fact it turns out that $\langle n_B \rangle$ is linearly related to n_F , i.e. $\langle n_B \rangle = a + b n_F$, and it can easily be shown that the estimate of b from a least squares fit is the same as that defined from the covariance (in the case of symmetric intervals of rapidity).

In Figure 22 the UA5 data [60,61] are compared with the ISR data [65] in the same three rapidity intervals, $0 < |\eta| < 4$, $0 < |\eta| < 1$ and $1 < |\eta| < 4$. In all cases the correlation increases with $\sqrt{s}$. Most interest has centred on the case $1 < |\eta| < 4$, since there is a gap of two units of rapidity between the two regions, and it is therefore unlikely that clusters of the type discussed under short-range correlations could give particles in both intervals. This correlation was small at ISR, but is now significant at the Sp̄pS. This might be thought to be evidence for a growing long range correlation.

Figure 22: Variation of the forward-backward correlation parameter, b , with $\sqrt{s}$

To understand these data it is helpful to recast the formula for b . The following identity may be shown to hold:

$$b \equiv \frac{D_S^2 / \langle n_S \rangle - 4 \langle d_S^2(n_F) \rangle / \langle n_S \rangle}{D_S^2 / \langle n_S \rangle + 4 \langle d_S^2(n_F) \rangle / \langle n_S \rangle} \quad (18)$$

where $n_S = n_F + n_B$. D_S^2 is the variance of the n_S distribution, and $d_S^2(n_F)$ is the variance of the n_F distribution at fixed n_S . The angle brackets denote averages over n_S . The first term in both numerator and denominator is determined merely by the overall multiplicity distribution. The second term reflects forward-backward fluctuations at fixed multiplicity. In a very naïve cluster model (clusters of fixed multiplicity and zero decay width randomly emitted into the forward and backward regions) this second term would just equal the cluster decay multiplicity κ . In a more realistic model one needs to allow for the width of the κ distributions, and for leakage effects which mean that not all decay products of a cluster fall into the selected rapidity region. It turns out that these two corrections act in opposite directions, and therefore roughly cancel. A more detailed discussion may be found in [60].

One can therefore recast the formula for b as:

$$b = \frac{(D_S^2 / \langle n_S \rangle - \kappa_{eff} \langle \kappa \rangle)}{(D_S^2 / \langle n_S \rangle + \kappa_{eff} \langle \kappa \rangle)} \quad (19)$$

where $\kappa_{eff} (= 1 + \langle \kappa(\kappa - 1) \rangle / \langle \kappa \rangle)$ takes account of the finite spread of cluster multiplicities. Note that κ_{eff} involves the same combination of moments of the κ distribution as was inferred from

the short range correlations. The term ζ_{leak} takes account of leakage effects, while the product $\kappa_{eff} \zeta_{leak}$ is of the same order as $\langle \kappa \rangle$. The value of κ_{eff} may be estimated from the data, and seems to be roughly independent of multiplicity and of $\sqrt{s}$, as we would have expected from the analysis of short-range correlations. The rise of b with $\sqrt{s}$ is thus seen to be due to the increase in the term $D_s^2 / \langle n_s \rangle$, which would rise like $\langle n_s \rangle$ if KNO scaling held exactly, or slightly faster in view of the observed scaling violations.

The observed forward-backward correlations therefore can be accounted for in terms of short-range correlations (clusters), together with the energy dependence of the overall multiplicity distribution. In one sense the growing correlation is seen to be a statistical effect; as $\langle n \rangle$ grows the fractional forward-backward fluctuations are reduced and a larger correlation is seen. Of course, the real question is why the multiplicity distribution is so broad, since this is the source of the correlations.[†] An impact parameter picture (see "Statistical models" below) gives a natural explanation for this, as a consequence of the fact that the colliding objects are extended. A large impact parameter will give low multiplicity (in both forward and backward regions), while a small impact parameter will yield high multiplicity (again in both hemispheres).

A systematic study of these forward-backward correlations has been made in [60], for example studying how the correlation strength varies with the size of the gap between the "forward" and "backward" regions. The correlation parameter has also been studied for asymmetric regions; for example a substantial correlation remains even when both regions lie within the same c.m. hemisphere.

Rapidity gap correlations

A recent ISR paper [66] has made an extensive study of rapidity gap correlations. Their conclusion was that two different types of cluster, one small and narrow, and the other large and broad, were required to describe the data. The UA5 Sp $\bar{p}$ S data have now been analyzed in a similar way [60], and have been shown to lead to a different conclusion; they are compatible with the UA5 cluster Monte Carlo program, which employs only one type of cluster, whose parameters are chosen to fit the short-range and forward-backward correlation data above.

The basic idea is to study the distribution, $F_k(G)$, of pseudorapidity gaps (G) between pairs of particles having exactly $k-1$ charged particles lying between them in pseudorapidity. A normalised correlation function is defined by

$$R_k(G) = F_k(G) / \tilde{F}_k(G) - 1, \quad (20)$$

where $\tilde{F}_k(G)$ is the distribution expected in the absence of correlations, which can simply be computed in terms of the single-particle rapidity distributions. The correlation function R_k is computed as a function of charged multiplicity, m , and then averaged over m to improve statistics. Some of these correlation functions are shown in Figure 23 for the 546GeV data. The curves show that the UA5 cluster model gives an excellent account of the data for all values of k . A similar conclusion holds at $\sqrt{s} = 200$ and 900GeV, with the same cluster parameters.

[†] For example random particle emission would give $\kappa_{eff} = 1$, $\zeta_{leak} = 1$ and $D_s^2 / \langle n_s \rangle = 1$ for a Poisson multiplicity distribution, and hence $b=0$. Indeed, in e^+e^- collisions the multiplicity distribution is not far from a Poisson, and the forward-backward correlations are small.

Figure 23: Rapidity gap correlations at $\sqrt{s} = 546\text{GeV}$, for several values of k .

Summary of correlations

Our main conclusion is that a common approach, in terms of a cluster model with $\langle \kappa \rangle \approx 2$, gives a satisfactory description of the correlation data at the Sp̄pS. The cluster parameters (multiplicity, decay width) do not seem to vary significantly over the Sp̄pS range. There may be some differences from ISR data, but it is hard to assert this with confidence given the differences between the experiments and their analysis techniques. The other necessary input in interpreting the data is the overall multiplicity distribution, and this is still not understood in any quantitative way. However, despite its success, a cluster model is not the only approach which can deal with these correlation effects, and some other models are discussed below.

One can also speculate on the nature of the "clusters". All we really learn from the data is their decay width ($\delta \approx 0.75$ units of pseudorapidity) and decay multiplicity ($\langle \kappa \rangle \approx 2$, if all-neutral decays are excluded), and the latter depends on the (unknown) decay multiplicity distribution. Clearly conventional resonances contribute to the clusters, but it is not clear that this is sufficient. An estimate of $\langle \kappa \rangle$ from resonance decays, based on extrapolating known yields of low mass resonances (i.e. 0^- , 1^- , 2^+ mesons and $\frac{1}{2}^+$, $\frac{3}{2}^+$ baryons) from lower energies and some plausible assumptions, arrives at ≈ 1.4 [60,67], and also too low a value of $\langle \kappa(\kappa-1) \rangle / \langle \kappa \rangle$. Maybe there are many higher mass resonances whose production we have no reliable means to estimate. Or maybe local quantum number conservation, as would occur naturally in a picture like the Lund string model, is responsible. Or maybe we need to allow for the emission of many soft gluons (like mini-jets, or of still lower p_T), which could well be approximated as clusters in a model such as described here.

DIFFRACTION DISSOCIATION

The subject of diffraction dissociation, or the quasi-elastic excitation of one beam particle into a relatively low mass state, has been studied at the Sp $\bar{p}$ S by UA4 [68,69,70] at $\sqrt{s}=546\text{GeV}$, and by UA5 (at 200 and 900GeV [71,72], building on earlier work at $\sqrt{s}=546\text{GeV}$ [5]). One should also mention the UA8 experiment which has recently started to take data [73], but the aim of this experiment is high- p_T diffraction, and therefore it lies rather outside the scope of the present article.

Single Diffraction

The UA4 and UA5 experiments have adopted very different techniques in their attempts to isolate single-diffractive (SD) events, i.e. those in which just one beam particle is excited. UA4 use events in which they detect the recoil $\bar{p}$ in their "pots", from which they measure the squared momentum transfer to the recoil particle, t , and its Feynman- x value, from which the recoiling mass, M , may be inferred (using $x_F \approx 1 - M^2/s$). They have two sets of data: high- t ($0.5 \leq |t| \leq 1.5\text{GeV}^2$) for which a good resolution in x is possible ($\approx 0.6\%$), and low- t ($0.04 \leq |t| \leq 0.35\text{GeV}^2$) which includes most of the cross-section, but where the resolution in x is poor ($\approx 8\%$). UA4 also detect some of the recoil particles in their own drift chambers and in UA2's central detector.

UA5 never detect the recoil particle, and so cannot measure M or t . Instead they exploit the different triggering characteristics of SD and NSD events (Figure 2). By using observed trigger rates for single- and two-arm triggers and using Monte Carlo estimates of trigger efficiencies they infer the cross-sections for SD and NSD events. Clearly the largest uncertainty in this method is in the models used for the Monte Carlo work.

The conventional picture of diffraction dissociation is that the cross-section should peak at small masses, given by the coherence condition $M^2/s \leq (m_p R)^{-1}$, where R is the interaction radius. Thus $M^2/s \leq 0.15$, though in practice the diffractive peak is usually clearly seen for $M^2/s \leq 0.05$, and this cut will be generally used in the data discussed below. Based on Mueller-Regge theory the dominant form of the mass distribution should be $d\sigma/d(M^2/s) \sim (M^2/s)^{-1}$. The pre-Sp $\bar{p}$ S data and many of the theoretical aspects are reviewed in ref [74].

Some of the UA4 high- t data [68] are shown in Figure 24. We note a number of important points. Firstly a clear peak is seen at small masses, which we associate with diffraction dissociation. The data fall steeply with $|t|$. The form of the mass spectrum is consistent with $1/M^2$, apart from low masses where the experimental resolution smears the data out. At fixed t the invariant cross section, $\frac{s}{\pi} \frac{d^2\sigma}{dt dM^2}$, scales with M^2/s from ISR to Sp $\bar{p}$ S energies. All these observations are in accord with expectations from Mueller-Regge theory.

UA4 have also studied the fragmentation or decay properties of the excited system [69] in their high- t data. They find that the pseudorapidity distributions of the recoil particles broaden with M in the way that would be expected for p_T -limited phase space fragmentation, but in conflict with a picture in which the particles are emitted isotropically. Furthermore, it appears that the average charged multiplicity depends on M^2 in the same way that $\langle n \rangle$ for NSD events depends on s . UA5 reach the same conclusion, but for the full t range. Instead of looking at different M -values they study different ranges of multiplicity, and compare with Monte Carlo calculations for p_T -limited and isotropic "decay" [5,71], as shown in Figure 25. Indeed, UA5 have been able to use the shapes of the pseudorapidity distributions to make a crude estimate of $\langle p_T \rangle$, quoting a value in the range 0.35 to 0.55GeV/c, thus very compatible with NSD events. Note that it is for the high masses (or multiplicities) that the conclusion about p_T -limited decays is clear, and the Sp $\bar{p}$ S has given us the opportunity to excite large masses diffractively (e.g. $M^2/s = 0.05$ corresponds to $M \approx 200\text{GeV}/c^2$ at $\sqrt{s} = 900\text{GeV}$).

Figure 24: UA4 high- t data. (a) Mass distributions, showing clear diffractive peaks. (b) Test of scaling in M^2/s at fixed t . (c) Showing the $1/M^2$ dependence of the cross-section.

Figure 25: Histograms of $\sigma_\eta = \sqrt{\langle (\eta - \langle \eta \rangle)^2 \rangle}$. (a) Single arm triggers in 546GeV UA5 data. (b) SD models with p_T -limited (solid) or isotropic (dashed) decay. (c) NSD background in the single-arm sample.

The estimation of the full cross-section for single-diffraction presents both experiments with difficulties, though. The UA5 method is simple in principle, but is dominated by systematic errors in the trigger efficiencies, owing to uncertainties in the models. There appear to be two main uncertainties. The first is the shape of the Feynman- x distribution for leading baryons close to $|x| = 1$ in NSD events, since an NSD event having a proton with $|x| \geq 0.95$ will kinematically fake an SD event, and thus needs to be subtracted. UA5 favour a $1 - |x|$ form, but there are no direct data on this point, and a flat distribution has also been considered. The second uncertainty is the M^2/s distribution for SD events at

very low masses, since such events are seldom detected. UA5 assume a $(M^2/s)^{-1}$ form right down to threshold. UA4's problem is that they have to use their low- t data, which have a very poor resolution on x (or M), and they therefore need to make cuts to separate SD and NSD events. They choose to make cuts on the rapidity gap between the recoil $\bar{p}$ and the closest recoil particle.

The published results on σ_{SD} are shown in Figure 26, with a compilation of lower energy data for comparison. We see that the UA4 and UA5 data are not in very good agreement, the UA4 point lying higher, though both have large errors. Several reasons for this may be suggested. The UA5 method explicitly subtracts any NSD events lying under the diffractive peak, whilst UA4 do not make such a subtraction, though they imply that their cuts reduce such background to a low level. However, this must be model-dependent, since kinematically there is no distinction between an NSD event with a proton at $|x| \geq 0.95$ and an SD event. Another possible explanation is that in order to fit their rapidity gap distribution UA4 needed to double the SD cross-section for $M^2 < 4\text{GeV}$ compared with a $1/M^2$ form. This corresponds to an extra $\sim 2\text{mb}$ of cross-section in a region where UA5 have low detection efficiency, and may go some way to reconciling the data. The best we can state at present is that the SD cross-section in the $\text{Sp}\bar{\text{p}}\text{S}$ energy region is $\sim 5-9\text{mb}$, and thus not much higher than at the ISR. We should also note, however, that the lower energy data, which again use a variety of different techniques, are far from being mutually consistent. It is evident that the SD process is not at all easy to identify experimentally, and therefore it is hard to draw conclusions about the $\sqrt{s}$ dependence of σ_{SD} . A constant cross-section cannot be excluded, though it looks as if there is probably a gentle rise. However, it seems clear that σ_{SD} is rising with energy much less rapidly than the elastic cross-section.

Figure 26: σ_{SD} vs $\sqrt{s}$. For sources of data see ref [71,70]

Double Diffraction

The process of double-diffraction (DD), in which both beam particles are excited into low mass states, is even harder to identify convincingly, but UA5 have made an attempt to estimate the cross-section [71,72]. The method is a simple extension of their SD procedure, by sub-dividing the two-arm trigger sample by some cut designed to enhance double-diffraction (e.g. requiring a large rapidity gap in the central region). They then use Monte Carlo simulations for SD, DD and non-diffractive (ND) events to deduce the proportions of each in the data sample. Clearly the results are dominated by systematic model uncertainties. The problem is that most DD events (with p_T -limited fragmentation) look very much like ND events, and therefore any cut designed to separate them has a low efficiency (or else a low purity). The results quoted by UA5 are $\sigma_{DD} = 4.0 \pm 2.5 \text{ mb}$ at $\sqrt{s} = 900 \text{ GeV}$, and $3.5 \pm 2.2 \text{ mb}$ at $\sqrt{s} = 200 \text{ GeV}$.

The DD cross-section may be predicted in terms of SD and elastic scattering if factorization of the diffractive vertices be assumed to hold. The following relations may be expected to hold [74]:

$$\sigma_{DD} = \frac{\sigma_{SD}^2}{4\sigma_{el}} \cdot \frac{b_{SD}^2}{b_{el}b_{DD}}, \text{ with } b_{DD} = 2b_{SD} - b_{el}, \quad (21)$$

where the b 's are the slopes of the t -distributions, assumed approximately exponential. If we take $\sigma_{el} = 13.6 \pm 0.6 \text{ mb}$, $b_{el} = 15 \text{ GeV}^{-2}$, $b_{SD} = 8 \pm 1 \text{ GeV}^{-2}$ and $\sigma_{SD} = 7 \pm 1 \text{ mb}$ we find that σ_{DD} should be in the region of 2–4 mb, not inconsistent with the UA5 estimate. So it appears that double diffraction is probably not a large part of the inelastic cross-section. Furthermore it is not clearly distinguishable from the non-diffractive events, which probably makes its neglect elsewhere in Sp $\bar{p}$ S analyses justifiable.

EXOTIC PHENOMENA

Centauro Events

Before the advent of the Sp $\bar{p}$ S our only information about particle interactions in this energy region came from cosmic ray experiments. A number of unusual phenomena have been reported in high energy cosmic ray data, of which the most spectacular and inexplicable are the "Centauro" events [1], observed in the Mount Chacaltaya emulsion chamber experiment, and recently by the joint Chacaltaya-Pamir group [75]. Among the striking features of these events are high hadronic multiplicity[†] and high p_T (around $1.7 \pm 0.7 \text{ GeV}/c$ is estimated). However, the most curious property of the Centauro events is the apparent absence of produced photons (and thus π^0). This has led to speculation that the produced particles might be baryons and antibaryons.

[†] The Centauro events are estimated to have a c.m. energy of around 1 to 2 TeV. The detection threshold of the experiment is around 1 TeV in the laboratory system, which means that the observed particles come from only a part of the forward c.m. hemisphere. The total hadronic multiplicity therefore depends on an extrapolation to the unseen part of phase space. The Chacaltaya group favour a "fireball" type model, and on this basis estimate a hadronic multiplicity around 100 [1], but an equally valid interpretation of the events is through a p_T -limited phase space model, which would lead to a much higher hadronic multiplicity, around 200 [78]. Another uncertainty in interpreting the Centauro events arises because only the electromagnetic part of a hadronic shower is detected. The fraction of a hadron's energy which goes into electromagnetic particles, k_y , depends on the particle type, being ~ 0.33 for pions, and ~ 0.2 for baryons. This leads to uncertainties in estimating the incident energy, and the $\langle p_T \rangle$ of the produced particles.

There are a number of other exotic types of event which have been claimed in these cosmic ray data, e.g. "mini-Centauros" (like Centauros, but of lower multiplicity), "Chirons" (high p_T , very narrow jets including hadrons) and "Geminions". There was therefore the hope, before the Sp $\bar{p}$ S started operation, that some very spectacular phenomena might be seen. It should be emphasized that the cosmic ray experiments are dealing with small numbers of events (up to a few hundreds) at these high energies, so that the exotic events should show up with large cross-sections if they exist, and therefore "minimum-bias" data is the appropriate place to look for them.

In the early 546GeV data both UA5 [55,67] and UA1 [76] made searches for Centauro events, with negative results. The UA5 method was to identify discrete photons via their conversions in a steel beam pipe. They then looked for events with high charged multiplicity and low photon multiplicity. In a sample of 3600 NSD events no events having the properties expected for Centauros were found. The UA1 study used a calorimetric technique. For each event they compared the energy in the first 4 radiation lengths of their calorimeters (which should be predominantly associated with electromagnetic particles) with the energy beyond 12 radiation lengths (mainly hadronic). Again the distributions looked normal, with no unexpected population of events in the region expected for Centauros, in a sample of 48000 events.

However, the Centauros seen in cosmic ray events were all at c.m. energy above 546GeV. Therefore this first negative result at the Sp $\bar{p}$ S might indicate a threshold just above. Indeed, a study of the $\sqrt{s}$ dependence of the various unusual events in the cosmic ray data [77] gave some indication of such a threshold, and suggested that at least some types of these exotic events should be produced at the 5–10% level if the Sp $\bar{p}$ S energy could be raised to $\sqrt{s}=900\text{GeV}$. This was in fact one of the main motivations for the Pulsed Collider run of 1985.

The UA5 detector was enhanced in two ways for the Centauro search at 900GeV. A "photon converter", shaped so as to give roughly uniform photon detection as a function of pseudorapidity, was placed between the beam pipe and the streamer chambers for certain runs, and a 90° calorimeter was installed to give some energy measurements, and in particular to detect neutrons or antineutrons which might be created in Centauro events. The UA5 900GeV analysis is presented in refs [78,49], using all the characteristic features of Centauro events: high p_T , high multiplicity and photon depletion. For example, Figure 27 shows plots of the number of observed photons against observed charged multiplicity for several event samples – for data at 900GeV, "normal" Monte Carlo and for a Monte Carlo representing the properties of Centauro events. Clearly the data look normal, and there is no population of events in the Centauro region; Figure 27 also shows a sample of events with a cut demanding high E_T in the UA5 calorimeter, which should enhance the proportion of Centauro events, but still there are no candidates. From these results upper limits on Centauro production were deduced, depending on the assumed $\langle p_T \rangle$, typically of the order of 1–4% of inelastic events at the 95% confidence level. In Figure 28 we show these limits. UA5 also searched in their single-arm triggers for possible diffractively excited Centauro events, but again with negative results.

How then are we to interpret the non-observation of Centauros at the Sp $\bar{p}$ S? Clearly there are several possibilities. We may simply not have reached sufficiently high c.m. energies at the Sp $\bar{p}$ S and have to await results from the Tevatron. Maybe the cosmic ray data or their interpretation are just wrong for some reason. Or maybe the cosmic ray events are not the result of hadron-hadron collisions. We know for example that the target is a nucleus, and so may be the projectile, though nuclei are not likely to penetrate so deep in the atmosphere, and also in this case we would expect to see some nuclear fragments, which would be of low p_T . Possibly the explanation lies with some exotic component in the cosmic ray spectrum, like globs of quark matter with nucleons accreted around them, as suggested in ref [79]. Another possibility is an anomalous interaction of multi-TeV photons [80], which could help to explain both Centauro events and some other anomalous effects in cosmic ray data.

Figure 27: Plots of observed photon multiplicity against charged multiplicity. (a) UA5 data at $\sqrt{s} = 900\text{GeV}$. (b) Normal Monte Carlo. (c) Centauro Monte Carlo. (d) Data having high calorimeter energy.

Figure 28: Upper limits (at 95% c.l.) on Centauro production at $\sqrt{s} = 900\text{GeV}$.

Free Quarks

Although present ideas based on QCD do not expect free quarks to be produced, it is clearly appropriate to search for such objects when a new accelerator opens up a new energy regime. At the Sp̄pS the UA2 collaboration has made such a search at $\sqrt{s} = 546\text{GeV}$ (see ref [81], updated with greater statistics in ref [82]). Their 90° spectrometer, installed for the early Collider runs, was

equipped with scintillation counter hodoscopes which were used to measure the ionization of produced particles. A maximum likelihood method was used to make the best estimate of the ionization based on the signals in seven or eight counters. The outcome was that no candidates having ionization less than 0.7 times that for a minimum ionizing particle were seen. From this upper limits on the production of free quarks were placed at the level of $2.8 \cdot 10^{-6}$ and $5.6 \cdot 10^{-5}$ per charged particle for charges $\pm 1/3$ and $\pm 2/3$ respectively (at 90% confidence level). These limits apply to very light quarks; since the study was made at 90° the momenta of the particles are low, and so the limits rise quite rapidly with mass.

Monopoles

A search for magnetic monopoles was made at the Sp $\bar{p}$ S by the UA3 experiment [83]. Their technique was to use sheets of plastic (kapton) in which the heavily ionising monopoles should leave tracks which were then developed by chemical etching. After etching the presence of small holes in the plastic sheets would signify the passage of monopoles. The plastic sheets were inserted both inside and outside the UA1 beam pipe, and also around the UA1 central detector, in the hope of tracking monopoles through the UA1 field. The result of this search was that no hole was found which could be attributed to the passage of a penetrating highly ionizing particle. From this upper limits on the production of monopoles were placed at around 10^{-32} cm^2 (at 90% confidence level). These limits are for low masses; for further details ref [83] should be consulted.

Rapidity Fluctuations ("Spikes")

It is not clear that this topic should be classified as "exotic". However, the results were thought by some to be surprising when they were first presented, and it was suggested that they might indicate the formation of "hot spots" of quark-gluon plasma. The explanation now appears to be more mundane.

The idea for this study by the UA5 experiment originated with a paper which suggested the possible emission of "gluon-Cerenkov radiation" in hadronic collisions [84], which would lead to the emission of many particles in a narrow rapidity interval, with no jet-like structure in the azimuthal angle. The experimental method is to take a fixed window in pseudorapidity, say $\Delta\eta = 0.5$, and for each event to find the position in rapidity where this window contains the largest number of particles, which is denoted n_{max} . In this way one finds the greatest local rapidity density of each event. In the UA5 data [85,86,5] events were seen in which up to 15 particles were emitted in a half unit of pseudorapidity, i.e. $dn/d\eta \approx 30$ or ten times the overall average. Some of these events look very striking; Figure 29 shows the rapidity distributions for a few such events. Furthermore, the particles show no jet-like clustering in azimuth, ϕ .

The question is then whether such events can arise simply as a result of random fluctuations, given the observed rapidity distributions and knowledge of short range correlations. The answer appears to be yes, based on a comparison with the UA5 cluster Monte Carlo, which incorporates these effects [54,29]. The Monte Carlo seems to generate "spike" events at a rate very similar to that seen in the data. A Monte Carlo spike event is shown in Figure 29. We could in fact have anticipated this from the agreement noted earlier between data and Monte Carlo for the high order rapidity gap correlations (section "Rapidity gap correlations"), since these correlations tell us about the probability of finding large numbers of particles in various small rapidity intervals. We therefore conclude that the spike events principally arise from the random superposition of particles and clusters.

The $\sqrt{s}$ dependence of these events has also been studied by UA5, and an interesting scaling behaviour was noted. In Figure 30 we show a plot of $\langle n_{\text{max}} \rangle$ against n_{ch} , for data at $\sqrt{s} = 200, 546$ and 900 GeV . All the data show the same behaviour. Furthermore, if a small subset of the data having high E_T in the UA5 calorimeter is used, the points still lie on the same curve. The ability of the UA5 Monte Carlo to reproduce these data is also shown in Figure 30.

Figure 29: Rapidity distribution of typical "spike" events. The solid histograms are data, and the open ones Monte Carlo, both at $\sqrt{s} = 546\text{GeV}$.

Figure 30: (a) Average "spike" multiplicity $\langle n_{\max} \rangle$ vs. n_{ch} . (b) 546 GeV data compared with the UAS Monte Carlo.

MODELS

The "soft-physics" data from the Sp $\bar{p}$ S have stimulated a great deal of theoretical activity, and in the present review it is impossible to give more than a superficial overview of the main types of model used. An attempt will be made to refer to many of the relevant papers, but the bibliography is certainly far from complete, and the author apologizes to those whose work he cannot include. Emphasis will be given to those models which have been directly compared to the Sp $\bar{p}$ S data.

In principle QCD should be able to predict all the data described above. In practice we have no precise way to make the calculations at present, and so a variety of approaches have been followed in an attempt to describe the data approximately. Of course these approaches are not orthogonal to each other — they are all trying to describe the same physics, and have many elements in common. We outline some of the main ideas here. In broad terms one can identify two approaches — a microscopic approach starting from quarks and gluons, and superimposing various configurations of partons to make up a hadronic collision, and statistical models of various kinds.

Microscopic models

One of the older and most complete approaches to the calculation of high energy soft processes is the **Dual Parton Model**, also often called the Dual Topological Unitarization (DTU) scheme. Early versions of this scheme [87] envisaged a colour separation in a hadron-hadron collision, leading to the formation of two chains or strings of hadrons: in the case of $p\bar{p}$ collisions a long $qq - \bar{q}\bar{q}$ chain and a short $q - \bar{q}$ chain.[†] The momenta of the partons at the ends of the chains are determined from measured structure functions, and the two chains are assumed to fragment independently, in the way observed in e^+e^- collisions or deep inelastic scattering. Thus in principle the model had no free parameters, just requiring measurements of structure and fragmentation functions. Furthermore, in principle the Dual Parton Model gives a complete description of soft hadronic processes, since any measurable quantity can be predicted given the parton distributions and a model for the chain fragmentation. For example, the model can easily be cast in the form of a Monte Carlo program to generate complete events.

However, early Sp $\bar{p}$ S data quickly revealed the need for development of the model, for example to fit the rising central rapidity plateau. The solution is to introduce extra chains of hadrons formed between sea partons. The additional chains contribute in the central rapidity region, and lead to the growth of the central plateau and $\langle n_{ch} \rangle$ and contribute to the tail of the multiplicity distribution. The two-chain picture may be shown to correspond to single pomeron exchange. In this analogy with Regge theory the multi-chain diagrams correspond to multiple Pomeron exchanges, and therefore the numbers of chains are taken from Reggeon Calculus calculations. This connection with S-matrix theory leads to the model satisfying unitarity in a satisfactory way.

Several groups have developed the model along these lines, and achieved reasonable agreement with the Sp $\bar{p}$ S data, such as average multiplicities, rapidity distributions (both inclusive and semi-inclusive), multiplicity distributions (including KNO scaling violations and the rapidity dependence of multiplicity distributions), and forward-backward multiplicity correlations [89,90,91,92,93,94,95]. A comprehensive tuning of the parameters of such a model to fit the UA5 data is described in ref [96]. Further modifications to the model were needed to account for the UA1 data on the p_T vs. n_{ch} correlation and "mini-jets". A solution is to give the partons at the ends of the chains some intrinsic transverse momentum, k_T [97,98], whose average, $\langle k_T \rangle$ has to increase with

[†] One prediction of this picture was for differences between pp and $p\bar{p}$ collisions, since in the former case two overlapping $q - qq$ chains would be formed. The early version of this model was shown to disagree with data [7], but the subsequent introduction of multiple chains led to a better description [88].

$\sqrt{s}$, to more than 1 GeV at the Sp $\bar{p}$ S. The origin of this k_T could be either semi-hard scattering [100,99] which can be explicitly grafted onto the model or multiple gluon emission, which seems to give very similar results [100].

Other models have been proposed which try to extend perturbative QCD methods into the soft physics region. For example, various soft-gluon bremsstrahlung or QCD branching models have been found to give a good description of the UA5 multiplicity distribution [101,102,103]. A considerable growth of activity in this field has, however, been stimulated by the UA1 mini-jet results, which naturally suggest that one could try to extend the successful QCD description of high E_T jets at the Sp $\bar{p}$ S collider down to lower transverse energies. The idea that a growth in parton-parton scattering could be linked to the growth of the total cross-section is not new [104]. The basic idea is that one could represent the total cross-section as:

$$\sigma_{tot} = \sigma_{soft} + \sigma_{jet}(p_T^{\min}) \quad (22)$$

where σ_{soft} is assumed constant with energy. Because of the large density of partons near $x=0$ the fraction that will scatter with $p_T > p_T^{\min}$ will grow with $\sqrt{s}$. A choice of $p_T^{\min}$ in the region 2-4 GeV/c seems to give a reasonable growth of σ_{tot} .

A number of recent papers have tried to estimate the effect of such "semi-hard" scattering. Qualitatively we can see that the jet events will have higher multiplicity and higher p_T and that the growth of such events could account for KNO scaling violations, and the correlation of $\langle p_T \rangle$ with multiplicity (e.g. refs [105,106]). A detailed study of charged multiplicity distributions in this picture has been given in refs [107,108,30]. For example, the idea in refs [108,30] is that the KNO scaling observed up to ISR energies is exact, and represents the behaviour of the soft component. One can then extract the properties of the jet events from the observed violations of KNO scaling at the Sp $\bar{p}$ S, and finds reasonable agreement with expectations. However, it should be pointed out that UA2 have studied in detail the changeover between hard and soft events in their data [109], and it is not clear that the data (on shape variables for example) in the intermediate region can be adequately described by a simple superposition of two independent models, of hard and soft events.

Perhaps the most complete approach of this kind, insofar as it is embodied in a complete Monte Carlo model which can predict any observed distribution, comes from the Lund group [110,111]. This is an extension of the Lund PYTHIA string model for high p_T processes. The basic idea is to calculate hard scattering above some cutoff $p_T^{\min}$, which is chosen to be around 1.6 GeV/c. With such a low cutoff the probability of multiple interactions becomes significant, especially at the highest Sp $\bar{p}$ S energies, and this is claimed to be an important factor in fitting the high multiplicity tail of the multiplicity distribution. The remainder of the total cross-section is made up of "soft" events, which are assumed to consist of two strings, rather as in the original version of the Dual Parton Model. The strings in the hard events are stretched in such a configuration that the two string picture is approached in the low p_T limit. The strings fragment according to the standard Lund scheme. A further significant feature of this model is that it takes into account the important impact parameter structure of hadron-hadron interactions. Since hadrons are extended objects, we may suppose that the probability for hard scattering(s) is much greater for small impact parameters than large. In this model a double-gaussian form of the impact parameter distribution is chosen to give the best fit to the data. In addition, diffractive events are incorporated, and found to be necessary in order to account for the observed yield of the low multiplicity events. After including all these (plausible) refinements reasonable descriptions of the data are found, including multiplicity distributions, forward-backward correlations and "spike events".

A different model of soft processes has also come from the Lund group, in the form of a program called FRITIOF [112,113]. Some years ago a version of the Lund model was proposed [114] consist-

ing of one string stretched between the colliding hadrons. This model worked well in the projectile fragmentation regions, but yielded too few particles in the central region. In the new model a hadron is treated like a vortex line in a colour superconducting medium. In a soft collision the hadrons overlap, and the net effect is to give two excited stringlike fields extended along the collision axis. These may then emit soft gluons, and fragment according to the standard Lund prescription. It is found that an adequate description of data can be found with just two strings; the additional strings which are required in the Dual Parton Model being effectively replaced by soft gluon emission. At present hard scattering is not included in this model, and this will clearly be needed to describe fully some features of the Sp $\bar{p}$ S data.

Statistical models

A wide range of geometrical and/or statistical approaches to multiparticle production in the Sp $\bar{p}$ S data can be gathered together under this heading. Several authors have emphasized the importance of the finite size of the hadrons, and thus of accounting for variations of collision properties with impact parameter (e.g. refs [115,116]). The general idea is that small impact parameters (central collisions) lead to violent collisions and high multiplicities, while large impact parameters (peripheral collisions) lead to small multiplicities. In contrast with pointlike e^+e^- collision process, the wide range of impact parameters in hadronic interactions leads to a much broader multiplicity distribution than in e^+e^- . Furthermore a peripheral collision will tend to give a low multiplicity in both forward and backward directions, while a central collision will give both high multiplicities. In this way strong forward-backward multiplicity correlations emerge naturally [116,117]. Other features of the data discussed in the context of this geometrical picture have been semi-inclusive rapidity distributions [118] and correlations between $\langle p_T \rangle$ and multiplicity [119] (on the supposition that higher hadronic temperatures are achieved in central collisions).

Another model which has been extensively compared with the Sp $\bar{p}$ S data is the "three-fireball" model of the Berlin group. Their basic idea is that in a hadronic collision some fraction of the energy of the incoming particles is effectively stopped, and forms a central fireball, while two more fireballs are formed by the excited projectile and target. In the original form of their model the three fireballs were taken to have equal energies, and the multiplicity distribution of their decay was computed by treating the excitation as two uncoupled harmonic oscillators [120,121]. This model gave quite a simple explanation of the multiplicity distributions up to ISR energies, both in the full phase space, where all three fireballs contribute, and in the central region, where only the central fireball gives decay products. In order to accommodate the UA5 observations of KNO scaling violations into this picture it appears necessary to assume that the fraction of energy going into the central fireball rises rather rapidly with $\sqrt{s}$ [122,123]. A number of other observations appear to have a statistical origin in this scheme, for example semi-inclusive pseudorapidity distributions [123] and the multiplicity distributions in limited rapidity regions can be well described [124,125], so can forward-backward multiplicity correlations [125], and even the difference between the multiplicity distributions in "jet" and "no-jet" UA1 data [126].

The UA5 results on fitting the Negative Binomial distribution to multiplicity distributions have stimulated a good deal of theoretical interest. This Negative Binomial distribution occurs in Quantum Optics, representing the distribution of photons from k independent sources (k is one of the parameters of the Negative Binomial (equ. (4)). Indeed, the distribution had been proposed for particle physics applications some years ago, based on analogy with these ideas, [27,26,127], and has recently been revived (e.g. the stochastic cell model of [28], which imagines particle emission from the surface of a small chaotic source). In this picture, then, the parameter k represents the number of sources (or phase space cells). In effect the Negative Binomial arises from the convolution of k independent Poisson distributions. It therefore seems reasonable that k should fall as the rapidity window is reduced, in accordance with observation. However, as $\sqrt{s}$ increases, the rapidity range grows, so one would naively expect the number of cells to increase, whereas in fact k falls with $\sqrt{s}$. Also in this picture it is not obvious how to interpret non-integer values of k .

Other authors have also pursued the analogy with Quantum Optics, and have particularly emphasized the rôle played by the inelasticity (or the leading particle effect) in hadronic collisions [128]. Their physical picture is that hadronic interactions are dominantly interactions of sea partons, while the valence quarks pass through unaffected and form the leading particles. In a statistical picture the average charged multiplicity should rise like $s^{1/4}$, much faster than observed. This can be accounted for if the inelasticity falls (and its distribution narrows) with increasing energy.[†] Of course the spread of inelasticities may just be another way of considering the spread of impact parameters discussed above. It is important to allow for the spread of inelasticities, which means that different events have different effective energies. In this picture, a reasonable description of the moments of the multiplicity distribution can be obtained with a single source [129]. A recent analysis along these lines of multiplicity distributions in different rapidity ranges has claimed to find evidence for two sources, one of which has bremsstrahlung-like behaviour, while the other has the properties expected for a quark-gluon plasma [130].

The Negative Binomial distribution is not the most general form of multiplicity distribution which could arise in these statistical approaches. A number of authors have suggested the use of the "Generalised Glauber-Lachs" (GGL) distribution (also known as the Perina-McGill distribution) [131], which takes account of both a coherent and a chaotic component in the particle emission. The Negative Binomial form is recovered in the case where the coherent component tends to zero. Recently an attempt has been made to fit the GGL form to the UA5 data [132]. The conclusion seems to be that the GGL formula does not give better fits than the Negative Binomial, which means that these data are not able to give meaningful information about the parameters of the GGL distribution, and specifically about the degree of chaoticity. Another extension of the Negative Binomial, the "Perina-Horák" distribution, has also been applied to the Sp $\bar{p}$ S data [133].

Another quantum statistical interpretation of the Negative Binomial distribution is in terms of partial stimulated emission [134]. In this picture particles may be emitted either independently or the emission may be enhanced by Bose-Einstein interference with particles already present. This model is shown to lead to a negative binomial multiplicity distribution, where the parameter k^{-1} is interpreted as the average fraction of the particles already present which stimulate the emission of an additional particle. This model has no problem with fractional values of k . Since the rapidity range of Bose-Einstein interference is presumably short, we may expect k^{-1} to be larger for small rapidity windows, and as the particle density rises with $\sqrt{s}$ then k^{-1} should rise with $\sqrt{s}$. Both of these expectations are in accord with observation. However, some more recent data give problems for the Stimulated Emission model. In a bubble chamber experiment at $\sqrt{s} = 22\text{GeV}$ it is found that k^{-1} is smaller by about a factor of 2 for the multiplicity distribution of negative particles than for all particles [135], whereas in the stimulated emission model k^{-1} should be greater since a larger fraction of the particles are able to cause stimulated emission in the negatives-only case. Further, it appears that when a cut on the azimuthal angle is made in the Sp $\bar{p}$ S data k^{-1} is essentially unchanged, [23,24], which is again hard to accommodate in the stimulated emission model.

A quite different source for a Negative Binomial distribution is also discussed in [134]. This is a sort of cluster model. The idea is that a Negative Binomial distribution can be formed by the convolution of a Poisson with a Logarithmic distribution. Clusters (more recently named "clans") are taken to be independently emitted with a Poissonian distribution, while the number of particles into which each cluster decays is assumed to follow a Logarithmic distribution (inspired by a cascade picture). This picture has no difficulty in accommodating the dependence of k^{-1} on rapidity and azimuthal cuts, and the behaviour for negatives-only. The parameters of the constituent Poisson and Logarithmic distributions may be inferred from data, and the surprising result is that the average number of clusters

[†] It may be interesting to note that a similar fall of inelasticity was required by the Wdowczyk-Wolfendale scaling idea alluded to under "PSEUDORAPIDITY DISTRIBUTIONS" above.

remains roughly constant (at about 8) from the ISR to the top of the Sp $\bar{p}$ S energy range. The size of the clusters (in both multiplicity and in rapidity spread) has to grow with $\sqrt{s}$. However, there seems no obvious reason for the number of clusters to be constant. It should also be noted that the convolution of Poisson and Logarithmic distributions is by no means the unique way to arrive at a Negative Binomial [136].

Finally it may be worth mentioning the UA5 cluster model GENCL [54,29,132]. It is perhaps presumptuous to call this a model, since its original purpose was to give an accurate simulation of the UA5 data in order to compute corrections, and therefore some experimental results were directly fed in as inputs; in some sense it is a "no-physics" model. However, since GENCL turns out to fit several features of the data which were by no means input there may be something to be learnt from it. It is basically a longitudinal phase space multi-cluster model. Data on the overall charged multiplicity distribution, p_T -distribution and rapidity distribution are essentially put in by hand, or parameters in the program are tuned to fit them. Particles are generated in clusters, decaying isotropically into around 2 charged particles, and leading particle effects are introduced. Energy and momentum are conserved. As seen above, this model gives a satisfactorily consistent description of the Sp $\bar{p}$ S correlation data. In addition it fits well the rapidity distributions at fixed multiplicity, the multiplicity distributions in different rapidity windows, the observed yield of "spike" events, and even to a surprising extent the rate of "mini-jet" events and most of their properties. What we should probably learn from this is that many of the pieces of data from the Sp $\bar{p}$ S are interrelated. Any model which fits the multiplicity distribution and has appropriate short-range correlations will probably also reproduce the long-range correlation data too, or if the multiplicity and rapidity distributions are well fitted then spike events will probably appear. The key feature of GENCL in fitting the multiplicity distributions seems to be cluster formation (a point also stressed in the "minimal model" of ref [137]), whilst the key to fitting the semi-inclusive rapidity distributions is mainly energy-momentum conservation. Therefore the success of this very simple ad hoc model in fitting the data (probably better than any of the "physics" models to date) should counsel us to take care in assessing which predictions of the models are really significant.

SUMMARY

In this short review we have endeavoured to give a general overview of the "soft physics" data from the CERN SPS collider, and a very brief sketch of some of the many models which have been put forward to try to account for these data.

In the early days, before the Sp $\bar{p}$ S started operation, there was much excitement and anticipation of exotic phenomena in this new energy regime, speculation fuelled by the Centauro and other bizarre events seen in cosmic ray data. Therefore the first results from the Sp $\bar{p}$ S looked disappointingly normal, lying on simple extrapolations from lower energy data. However, more careful study of the data revealed a number of interesting and unexpected features. Among these we may list the following:

- The violation of KNO scaling, particularly for the full phase space, but now established in other kinematic regions too.
- The strong rise of $\langle p_T \rangle$ with $\sqrt{s}$ above ISR energies, especially for heavy particles, kaons and baryons.
- The marked correlation between $\langle p_T \rangle$ and multiplicity.
- The observations of "minijets" by UA1.

- Strong growth of "long range" forward-backward multiplicity correlations (though in a cluster model this seems less surprising, being a statistical effect linked to the development of multiplicity distributions).
- The impressive success of the negative binomial distribution in fitting all charged multiplicity distributions.
- The apparently small value of the single-diffractive cross-section, though this has proved a difficult measurement, and the experiments do not agree too well.

In addition, there is still no evidence for any of the exotic event classes claimed by cosmic ray experiments.

These new experimental results have encouraged an extensive revival of interest in theoretical models of soft processes. The experiments have now almost finished their work (for soft physics). Indeed the Sp $\bar{p}$ S experiments may be the last generation of experiments to study complete events in this way, since the acceptance of detectors at the SSC (or LHC) will certainly be confined to the central region, and the same is largely true for the Tevatron Collider. However, an understanding of soft physics is of importance for these very high energy colliders, since multiple soft events could be an important source of background. Therefore for this reason if no other theoretical work is likely to continue for some time.

We now have several complete QCD-inspired models (complete in the sense that they are cast in a Monte Carlo framework and can predict any observed distribution) which give a reasonable description of most features of the data; notably the various versions of the Dual Parton Model model, and two derivatives of the Lund string model. These have many features in common, needing two long strings or chains, together with some additional source of central production, either additional chains or soft bremsstrahlung of gluons. All these models indicate the importance of "semi-hard" scattering at Sp $\bar{p}$ S energies, which helps to account for the first four of our "unexpected" results above. In addition there are many interesting ideas in the statistical approaches, and again many recurring themes, such as the need to allow for clustering, and the importance of taking into account leading particle effects (e.g. via the impact parameter dependence, or the spread of inelasticities). We may hope that these data from the Sp $\bar{p}$ S will constitute a useful basis for theoretical work for some years yet.

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