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ANALYSIS OF THE HADRONIC FINAL STATES AT
THE CERN SPS $\bar{p}p$ COLLIDER

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INTRODUCTION

This lecture covers new results on some selected soft processes from the CERN SPS antiproton-proton collider in experiments UA1, UA2 and UA5. The new energy regime of the collider has opened the possibility to further explore phenomena already seen at the CERN-ISR or at fixed target accelerators and to find or search for new phenomena.

The first section contains a presentation of the remarkable result that the average transverse momentum in the central region increases with the multiplicity, presents rapidity distributions where a noticeable plateau has developed and, finally, gives the charge particle multiplicity distribution and its moments. The question of KNO scaling will be addressed and evidence for scaling violation presented. In the second section charge particle correlations in rapidity will be presented. The analysis leads to the conclusion that small groups of resonances (clusters) are being produced.

In the last section some results on the production of identified particles will be given, including an estimate of the average particle

content of an event.

1. GENERAL FEATURES

1.1. Experimental Details

When comparisons are made with lower energy data, one has generally available proton-proton reactions at ISR and fixed target experiments, whereas the new 540 GeV (c.m.s.) data refer to anti-proton-proton collisions. This does not prevent meaningful comparisons since at 540 GeV the expected differences between $\bar{p}p$ and pp reactions are very small, ($\Delta\sigma/\sigma \approx 0.001$). Several experiments at ISR have compared $\bar{p}p$ and pp reactions at the same energy and found no large differences¹.

The data refer to the most common type of events, namely inelastic collisions, generally of rather high multiplicity. The average multiplicity of all particles is about 46 out of which 28 are charged particles. The fluctuations are large and there are different kinds of experimental difficulties when the multiplicity is very high (secondary nuclear and γ -conversion interactions in the beam pipe and in the detector material) or is very low (acceptance losses). Each experiment has set up a minimum bias trigger which is based on signals from a set of counters in which hits in coincidence with a beam crossing are required. The larger part of the solid angle is covered by the trigger counters, the smaller will be the necessary corrections. In azimuth the coverage is generally 2π in angle, whereas in polar angle θ (or pseudorapidity $\eta = -\ln \tan \theta/2$) the coverage is less complete although generally large. The situation is summarized in Fig. 1 for the three experiments discussed, all of which have two arms - one downstream from the proton direction, the other downstream from the antiproton direction. The lay-out of UA1, UA2 and UA5 are as in Figs. 2-4. The beam pipe obscures the very forward and backward regions. Other construction features leave dead angles, which all detectors aim to make small. In the case of UA5, the team I

Fig. 1 Coverage in pseudorapidity of minimum bias triggers in the three experiments UA1, UA2 and UA5.

belong to, the two streamer chambers are very long (6 m) and wide (1.25m). The necessary gap between them for the beam pipe is only 9 cm, small enough to allow some strange particles to reach and decay in the sensitive volume. The geometrical acceptance of such a set-up is about 95% for polar angles $\theta > 5.7^\circ$ (or pseudorapidity $|\eta| < 3$) and falls gradually to zero at $\theta = 0.8^\circ$ (or $|\eta| = 5$). The trigger accepts most of the inelastic events ($\sigma \approx 53$ mb) and no elastic events, for which according to UA4 and UA1,² $\sigma = 13$ mb. There is one class of inelastic events which requires special attention, namely single diffractive events. One of the beam particles then remains in the beam pipe. A trigger which requires at least one hit in each arm will obviously not accept most of the single diffraction events. A single arm trigger with a veto in the other arm is a complement which has been used (caution is needed, since beam-restgas collisions represent a background). From the above it should be clear that corrections are needed to the raw data. Monte Carlo programmes have been developed and tuned to represent the data sufficiently well to serve the purpose of making reliable corrections. For example, the minimum bias 2-arm trigger of UA5 is estimated to accept 96% of the inelastic non-single diffraction events and about 10% of the single diffraction events (which are about 18% of all inelastic events)³. The UA1 detector has a huge magnetic field and is equipped with calorimeters for both electromagnetic and hadronic

Fig. 2. The UA1 detector with its large dipole magnet (0.7T), central tracking detector and calorimeters.

Fig. 3. The UA2 detector with magnetic spectrometers in the forward and backward cones, central tracking detectors and calorimeters.

Fig. 4. The UA5 detector with its two large streamer chambers viewed each by three cameras. Counter hodoscopes used for triggering.

showers⁴. The UA2 detector⁵ has good electromagnetic calorimeters and a toroidal magnetic field in the end-caps. Both have tracking counters placed before the calorimeters as viewed from the interaction point. The UA5 detector is a visual (photography) tracking device⁶ without a magnetic field and calorimeter (later a small calorimeter was added). One can still in certain cases measure or indirectly infer momenta of particles as we will see.

1.2. The Theoretical Framework.

As is well known no fundamental theory is at present capable of dealing with soft processes. It is generally assumed that the parton model with quarks and gluons is the appropriate and correct picture. As perturbative QCD is not applicable in the domain of soft processes, one finds various phenomenological approaches in the literature. A physical picture for non-diffractive reactions which was advanced almost ten years ago⁷ views the processes in the following way: (i) the gluon sea is excited, (ii) the valence quarks pass through. Hadronization of the gluon sea produces hadrons in the central region. The valence quarks give rise to the leading particles and to hadrons in the fragmentation regions. In the multiperipheral model the central particles come from several strings (chains)⁸. These pictures are given as background for the way one might view these processes. Hadronization as a general phenomena has been emphasized by the group of Zichichi,⁹ who compares different processes (pp , $\bar{p}p$, e^+e^- , νN) at the same available energy for particle production, i.e. by removing the leading particles and subtracting their energies. At the SPS $p\bar{p}$ collider no data exist for such a comparison.

1.3. Transverse Momenta of Charged Particles.

One of the established experimental facts of high energy physics is the limited transverse momentum (p_T). At the CERN $p\bar{p}$ -collider UA1 has found a new effect which is seen in the Figures 5, 6 and 7.

Fig. 5 The distribution in transverse momentum of charged hadrons (UA1). For comparison ISR results (lower curve).

The invariant cross-section for both charged and neutral particle production is much larger at high p_T than at ISR energies and of a different shape. The result¹⁰ can be well described in the observed region of p_T by the form

$$\frac{E}{d^3p} \frac{d^3\sigma}{d^3p} = A \left(\frac{p_T}{p_0} + 1 \right)^{-n}$$

with $n \simeq 9$, $p_0 = 1.3$ GeV/c. This leads to an average $\langle p_T \rangle = 0.42$ GeV/c.

The new effect is that the spectrum changes shape with particle density in the central region. The curves for the three densities 2.4, 5.7 and 10.2 charged particles per unit of rapidity (the average density is 3.3), are shown in Fig. 6.

The new effect is shown in a more condensed form in Fig. 7, where one sees that the average transverse momentum increases with increasing particle density to a levelling off at $\langle p_T \rangle = 0.47$ GeV/c. A

Fig. 6 The distribution in transverse momentum for different multiplicity densities in the central plateau, (UA1).

Fig. 7 The average transverse momentum of charged particles vs the multiplicity density, (UA1).

similar behaviour at the ISR, but less pronounced, was reported at the Brighton Conference this summer¹¹. This phenomenon has no definite theoretical explanation, but will certainly attract attention and more study. Whether it can be viewed as a signal of the presence of a quark-gluon plasma state of matter was discussed by L. Van Hove¹². Some theoretical arguments have been advanced that at high energy densities, a phase transition to this kind of plasma should occur when the temperature exceeds a critical value¹³.

1.4. Rapidity Distributions

Another new phenomenon is the still increasing particle density (number of particles produced per unit of rapidity). The definition of rapidity is $y = 1/2 \ln (E + p_{\parallel}) / (E - p_{\parallel})$, of pseudorapidity (η) is $\eta = - \ln \tan \theta/2$, where (E , $p_{\parallel}$ and θ) are the energy, longitudinal momentum and polar angle of a produced particle. For massless particles the two concepts are identical and for energetic massive particles ($p \gg m$) almost the same. At the ISR the density of charged particles per unit of pseudorapidity (at 90° to the beam axis) is at most about 2 and is increasing slowly over the ISR range of energies¹⁴. The value at 540 GeV is about 3. Figure 8 shows the pseudorapidity distribution for charged particles as measured by UA1 and UA5, showing good agreement^{15,16}. A central plateau is clearly

Fig. 8 The distribution in pseudorapidity (folded around $\eta = 0$, i.e. 90° in c.m.s.) for inelastic events with single diffraction excluded. The UA1 and UA5 data are at the SPS $\bar{p}p$ collider (540 GeV), the R703 at the ISR (53 GeV).

developed. The same figure shows data at one ISR-energy (53 GeV)¹⁴. The above mentioned rise of the central density is approximately linear in $\log s$ as is seen in Fig. 9. Since Feynman scaling would require a constant density, scaling is clearly violated. No prediction exists whether this rise should level off or continue.

1.5. The Average Charged Particle Multiplicity.

Since the available rapidity range increases as $\ln s$, Feynman scaling predicts the average multiplicity to increase linearly in $\ln s$. The observations deviate also from this behaviour in that an

Fig. 9 The central multiplicity density at FNAL, ISR and $\bar{p}p$ Collider energies. The UA1 and UA5 measured points are for non-single diffractive events; the lower energy points are for inclusive data to be compared with the corrected data point, inclusive UA5.

important $(\ln s)^2$ -term is needed to describe the energy dependence of the average multiplicity. At ISR energies the coefficients in the expression $\langle n \rangle = a + b \ln s + c (\ln s)^2$ were found to be, $a = 0.88$, $b = 0.44$, $c = 0.118$. The corresponding curve is displayed in Fig. 10 together with UA5 results for the average charge particle multiplicity at 540 GeV. It is to be noted that the curve refers to inelastic events, i.e. including single diffractive events. At the SPS collider UA5 has recently measured the single diffractive component using a single arm trigger. Adding this component to the non single-diffractive one leads to a lowering of the average multiplicity (both data points are given in Fig. 10). The same curve also well describes the new result. It is of interest to note that at 540 GeV the $(\ln s)^2$ -term is responsible for most (67%) of the multiplicity. In a recent paper¹⁷ R.V. Gavai and H. Satz have compiled predictions at 540 GeV of four models, all with free parameters fitted to lower energy data. The Fermi/Landau thermodynamical model, in which the

Fig. 10 The energy dependence of the average charged particle multiplicity. The curves are fits to data up to the ISR energy range.

relation $\langle n \rangle = A \cdot s^{1/4}$ should hold, predicts too high a multiplicity, as can be seen in Fig. 11. The uncorrelated jet model of Van Hove 1964, for which Engels and Satz obtained $\langle n \rangle = A \ln s + B + C (\ln s)^{-1}$, leads to too low a value. A model with dominance of soft pion emission leads to a value in good agreement with the inelastic data point of UA5. This model has the energy dependence $\langle n \rangle = a + b \ln s + c \ln^2 s$. The curve $\langle n \rangle = A e^{1.7 \sqrt{\ln s}/\Lambda^2}$ suggested by QCD calculations (extrapolated into the soft region) goes somewhat high at 540 GeV but fits well the UA5 non single-diffractive point, i.e. inelastic with single diffraction subtracted. However, since the parameter was fitted to inelastic data at lower energies the agreement is somewhat fortuitous. Models should be tested in many ways, but at

Fig. 11 Extrapolation of four theoretical curves for the average charge particle multiplicity, fitted to inelastic data up to the ISR energies.

UJM = Uncorrelated jet model, QST = Model with Soft pion dominance, QCD = Quantum chromodynamical extrapolation to the soft region, Fermi = Fermi-Landau thermodynamical model.

this stage it seems unavoidable to conclude that the first two models have failed this test.

1.6. The Multiplicity Distribution.

The discussed average multiplicity is only the first moment of the multiplicity distribution. Fluctuations in multiplicity are measured by the second moment (D_2^2) and higher moments. As is well established, at lower energies the dispersion D_2 grows linearly with the average multiplicity¹⁸ rather than being proportional to $\langle n \rangle^{1/2}$ as for a Poisson distribution. The Koba, Nielsen, Olesen¹⁹ scaling conjecture implies that all higher moments are proportional to $\langle n \rangle^k$ where k is the order of the moment in question. These authors introduced a scaled variable $Z = n/\langle n \rangle$ and predicted that at very high energies the scaled probability $\langle n \rangle^{-1} P_n$ for n -particles should be equal to a universal, energy-independent function, $\psi(Z)$. Their argument was based on Feynman scaling. Although Feynman scaling is clearly violated, the KNO scaling has been less clearly violated so far. The UA1 group has reported KNO-scaling to hold in the central region even up to 540 GeV²⁰. The UA5 group, on the other hand, has found KNO scaling to be violated at 540 GeV for the full phase space region²¹.

In the theory KNO scaling is a limiting property valid at asymptotic energies. In practice, experimental data become available at successively higher energies. Approximate KNO scaling was found to hold from about 10 GeV c.m.s. energy in pp collisions²² up to the then highest available energy, 28 GeV ($= \sqrt{s}$). It was first found by A. Wroblewski²³, that for KNO scaling to hold, one should subtract leading particles. He found that $D_2 = \omega(\bar{n} - n_0)$, where $n_0 \sim 1$ is taken to represent the average number of charged leading particles. It has also been argued that single diffraction events should be eliminated. If so, KNO scaling could eventually be expected to hold more accurately for the non single-diffractive component, which at highest energy is the dominating one (about 85% of the inelastic

Fig. 12 The distribution of charged multiplicities at 540 GeV c.m.s. energy (UA5).

- a) observed; (insert: Monte Carlo results for the relation between true and observed number of charged tracks).
- b) fully corrected distribution.

Curves are predictions if KNO scaling holds, dashed line from ref. 22, solid line new fit by UA5 to non-single diffractive data.

Fig. 13 The relation between the first two moments (D_2 and $\langle n \rangle$) of the distribution of charged multiplicity. The straight lines are fitted to data at ISR energies and below.

cross-section). New data at several ISR energies were presented recently at the Brighton Conference²⁴. Particularly in the non single-diffractive component, one does find energy independent shapes of the scaled multiplicity curves. This means that no KNO scaling violation has been seen up to 60 GeV C.M.S. energy in pp collisions. The CERN $\bar{p}p$ Collider gives an order of magnitude higher energy. The UA5 group has measured the multiplicity distribution with its two large streamer chambers. The result, after corrections for acceptance losses, secondary interactions, trigger biases etc, is given in Fig. 12.

The curves are predictions from fits to data at lower energies based on the assumption that KNO scaling holds. A clear violation of KNO scaling is seen for the non-single diffractive component. The scaling violation is, of course, reflected into the moments of the distribution. The second moment, D_2 vs $\langle n \rangle$, is shown in Fig. 13, where KNO scaling would require all data points to lie on a straight line (in the ideal KNO-scaling the line should pass through the origin). Another way to quantify the violation of scaling is to give the fraction of events in the high multiplicity tail. At the ISR-energies (< 60 GeV c.m.s. energy), where scaling seems to hold, the tail beyond $Z = 2$ comprises 2.2 % of the events, whereas UA5 finds 6% in this region at 540 GeV c.m.s. energy.

As mentioned, UA1 has reported KNO-scaling to hold for the central region. Results from this detector have been given for the restricted ranges $|\eta| < 1.5$ and $|\eta| < 3.5$ but not for the full phase space. When a comparison is made with ISR data, a similar restricted phase space region is chosen. KNO-scaling holds approximately as is seen in Fig. 14. (NOTE ADDED: The UA5 group has, by restricting the phase space to $|\eta| < 1.5$ in a similar fashion, also found a similar result.)

1.7. KNO Scaling in Models.

When KNO scaling seemed to hold at lower energies, several models were constructed to account for this behaviour. Without being complete I list here some of these models together with other models which contain violation of KNO scaling.

I. MODELS WITH KNO SCALING

- (a) Unitary uncorrelated cluster model²⁵
- (b) Geometric-dynamic model^{26, 27, 28}
- (c) QCD jet calculus²⁹

II. MODELS WITH SCALING VIOLATION

- (a) Dual parton model^{30, 31}
- (b) Soft QCD Bremsstrahlung³²
- (c) Three independent "fireballs" model³³
- (d) Quantum Statistical or Chaotic Source model³⁴

One should add that some models with KNO scaling are flexible and can be modified to accomodate scaling violation. Several models with KNO scaling violation show the wrong behaviour in that they predict a narrower curve (smaller $D/\langle n \rangle$) at higher energy. Two models show

Fig. 14 The KNO scaled multiplicity distribution in the central plateau region (UA1). Curves fit lower energy data well, dashed line FNAL energies, solid line ISR energies.

a scaling violation of the observed type, the dual parton model by Kaidalov and Ter-Martirosyan³⁰ and also the Three Source Model by Liu and Meng³³. The Quantum Statistical or Chaotic Model, advanced by Knox³⁴ in 1974 already and recently by Carruthers et.al.³⁴, is simple in that it is based on the principle that no detailed dynamics need be specified. The model leads to a discrete multiplicity distribution with two parameters which is known in physics as the Bose-Einstein distribution, in statistical mathematics as the negative binomial (or Pascal's distribution). This model does not have KNO scaling. The mentioned authors, however, interpret the free parameter such as to lead to the wrong behaviour of the scaling violation. As will be shown below there is a connection possible to the Three Source Model³³. It leads to accidental approximate scaling in the ISR energy range and scaling violation of the correct type at 540 GeV. The model has asymptotic scaling at much higher energies where only one fireball (the central region) is assumed to dominate.

The Bose-Einstein distribution, first derived by Planck (1923)³⁵, was introduced in particle physics by Knox (1974)³⁴ and recently revived by Carruthers et al (1982)³⁴. It is a discrete distribution in n given by

$$P_n = \binom{n+m-1}{m-1} \left(\frac{\bar{n}/m}{1+\bar{n}/m} \right)^n (1 + \bar{n}/m)^{-m}$$

where there are two parameters; $\bar{n}$ being the mean value of n , which in this model is taken from experiment, and m . The meaning of m is interpreted differently by Knox (number of independent phase space cells) and Carruthers et al (number of independent chaotic sources). Both authors suggest that m increases with energy, leading to KNO scaling violation of the wrong type. At high enough mean values ($\bar{n}$) the distribution can be approximated by a continuous one,

$$\bar{n} P_n \rightarrow \psi(z) = \frac{m^m}{(m-1)!} z^{m-1} e^{-mz}$$

($Z=n/\bar{n}$) as has been pointed out³⁶. Obviously asymptotic scaling would require the parameter m to be constant. Fits to data show m to decrease with energy ($m = 8, 4.5$ and 4.0 at c.m.s. energies 24, 63 and 540 GeV, respectively)⁴⁷.

A transition to the Liu and Meng model is obtained if for each source one assumes $m = 2$, asymptotically represented by $\psi(Z) = 4 Z e^{-2Z}$. This is the input distribution for each of three independent sources - two fragmentation sources and one for the central region. The sources have different average multiplicities $\bar{n}_1 = \bar{n}_2$ (fragmentation) and $\bar{n}_3$ (central).

One can show that if several independent components contribute to the multiplicity, i.e. $n = \sum_i n_i$, and each component exhibits KNO scaling, then for the total distribution to KNO scale, it is required that the ratios $\bar{n}_i/\bar{n}$ ($i = 1, 2, \dots$) are energy independent.

Scaling violation is obtained by assuming different energy variations for at least one $\bar{n}_i$. This is what Liu and Meng do. In particular, the fragmentation regions are assumed to stop increasing somewhere in the ISR energy range, when $\bar{n}_1 = \bar{n}_2 = 3.4$ charged particles. At asymptotic energies only one component dominates, the central one, and then the limiting distribution returns to the input distribution, $\psi(Z) = 4Ze^{-2Z}$ which is very wide with $D/\langle n \rangle = 1/2 = 0.71$. Data at ISR has $D/\langle n \rangle = 0.45$ and at the SPS Collider $D/\langle n \rangle = 0.54$ for inelastic events excluding single diffraction. It is of interest to note that the UA1 central ($|\eta| < 1.5$) region distribution (most of the fragmentation regions excluded) has $D/\langle n \rangle = 0.66 \pm 0.02$ not far from the limiting case. Also the form $(4Ze^{-2Z})$ seems to represent the UA1 data well. At intermediate energies the simple three source model is mathematically more complicated (a sum of two exponentials in Z , each multiplied by a different low order polynomial in Z), but with only one energy dependent parameter, namely $\bar{n}_3/\bar{n}$. The mathematical complication disappears if all three sources are of equal strength

($\bar{n}_1 = \bar{n}_2 = \bar{n}_3$). In this case the overall distribution is a negative binomial with $m = 6$ (in agreement with fits to ISR data at $\sqrt{s} = 31$ GeV), which approximates to $\psi(Z) = 1944/5 Z^5 e^{-6Z}$.

2. CORRELATIONS

At lower energies it has long been known that the observed charged particles, most of which are pions, are to a large extent produced indirectly as decay products of resonances (ρ , ω , K^* etc). In experiments with many final state particles or in which no momentum measurements and particle identification have been made, one can resort to correlation studies. These are of two types - short-range correlations and long-range correlations. The "range" refers to distances in rapidities or pseudorapidities (η).

Fig. 15 Two-particle correlation in pseudorapidity showing typical short range correlation of about one unit of pseudorapidity.

2.1. Short Range Correlations.

If one particle is produced at η_1 , another at η_2 , the distance is $(\eta_1 - \eta_2)$ between them. It is useful to keep in mind that the decay of a neutral ρ -meson of typical momentum produces two charged pions at a distance of about one unit of rapidity.

One can define a correlation function $C_n(\eta_1, \eta_2)$ which depends on the charged multiplicity (n). By averaging over an interval in n one can increase the statistics. Since theory makes $C_n \propto 1/(n-1)$, one takes $\langle C_n(\eta_1, \eta_2) \cdot (n-1) \rangle$ and averages further over a region in (η_1, η_2) space, keeping the distance $(\eta_1 - \eta_2)$ fixed. The result of one such analysis is shown in Fig. 15. Curves for other multiplicities are quite similar to a first approximation.

The conclusion is that one observes clearly a correlation of a range in $\Delta\eta$ typical of small mass resonance particles (ρ , ω , K^* ...), namely of about one unit in pseudorapidity. One can further from studies of the height and width find the average size of the cluster of particles that produces this correlation. It is not immediately obvious that not groups (clusters) of particles larger than just resonances are responsible. Such studies are under way within the UA5 group, but here I can state that the sizes are about 2 charged particles.

2.2. Long Range Correlations.

If only small sized clusters of small mass were initially produced at first sight, it would seem natural that particles with distances > 2 units in pseudorapidity be uncorrelated. That this is not so was shown in experiments³⁷ at ISR. A similar and stronger long range correlation has been observed at the SPS collider by the UA5³⁸ and UA1 groups³⁹. In these studies, one observes the number (n_F) of charged particles in a forward interval, say, $0 < \eta < 4$, and the number

(n_B) of charged particles in a symmetric backward interval, $-4 < \eta < 0$. If the joint distribution $f(n_F, n_B)$ does not factorize into $f(n_F) \cdot f(n_B)$ then a correlation exists. Experimentally one studies the average of one of the variables (say n_B) at fixed n_F as a function of n_F . If factorization holds, the resulting $\langle n_B(n_F) \rangle$ is independent of n_F . Empirically it turns out that the quantities are linearly related, thus

$$\langle n_B(n_F) \rangle = a + b n_F$$

The slope b is taken as a measure of the correlation strength. Factorization (uncorrelated n_F, n_B) implies $b = 0$ (note, however, that $b = 0$ does not necessarily imply uncorrelated variables). Another closely related measure is the usual correlation coefficient ρ which is defined as

$$\rho = \frac{\text{cov}(n_F, n_B)}{\sqrt{\text{var } n_F \cdot \text{var } n_B}}$$

In the case where symmetry holds between the two hemispheres, one has $\text{var } n_F = \text{var } n_B$ and then $\rho = b$ (if b is determined by a least squares fit where each event is given the same weight). In the ISR energy range $b = 0.2-0.3$, whereas at the SPS collider $b = 0.54 \pm 0.01$ is reported by UA5. There is agreement between the b -values measured by UA1 and UA5. Fig. 16a shows the result together with the earlier ISR data. The increase of the strength with energy is clearly demonstrated. However, one can suspect that the effect is due to short range correlations. Clusters produced near the centre can emit decay products into both regions. In order to decouple from this effect one opens up a gap between the forward and backward regions. A study shows that a gap of $\Delta\eta = 2$ units of pseudorapidity is sufficient. The correlation strength (b) is reduced, Fig. 16c, but not to zero. At the SPS collider $b = 0.41 \pm 0.01$ remains, only at the lower range of ISR energies is $b \approx 0$. The explanation could be very simple. One does not have to introduce any specific, dynamical long range correlation. It is just unlikely that fluctuations (up or down from the average number of particles) in one region (F) are not accompanied by similar fluctuations in the other region (B). How this

suffices to explain the effect will be described below.

Fig. 16 The long range multiplicity correlation parameter b in dependence of energy

a) forward region $0 < \eta < 4$, backward $-4 < \eta < 0$.

b) central part with $0 < |\eta| < 1$.

c) with a central gap in η ; forward region $1 < \eta < 4$, backward $-4 < \eta < -1$.

Data are from the ISR experiment R701 and SPS Collider experiment UA5. The curves are Monte Carlo simulations with an average cluster size of 2 charged particles.

In Fig. 17 is given the two-dimensional empirical distribution (scatterplot) of the variables n_F and n_B . (The definitions of regions F and B are in terms of intervals in pseudorapidity η).

Fig. 17 Forward-backward multiplicity correlation for the case $0 < |\eta| < 4$.
a) the two-dimensional multiplicity distribution with n_F charged particles emitted forward, n_B backwards. The size of the small areas is proportional to the number of events with a given (n_B, n_F) .
b) the average n_B for fixed n_F , i.e. $E(n_B/n_F)$ in dependence of n_F .

The figure also shows how remarkably close to a straight line the averages lie. By introducing new coordinates ($n_s = n_F + n_B$ and $\Delta = n_F - n_B = 2n_F - n_s$), one has a joint distribution $f(n_s, n_F)$ and can sum over the variable Δ (or n_F) at fixed n_s to obtain the distribution of multiplicity n_s . The first two moments of this distribution are represented by the mean, $\langle n_s \rangle$, and the dispersion D_s . This distribution is thus obtained by projecting all events onto the 45° diagonal of the scatterplot. At fixed n_s the distribution in n_F $f(n_F | n_s)$ is of interest, since it describes how the n_s particles are shared between the forward and backward regions. The mean of n_F (given n_s) is by symmetry $= 1/2 n_s$. The first interesting moment is the squared dispersion, $d_s^2(n_F)$. One can show that the following identity holds:

$$b = \frac{1/4 D_s^2 - \langle d_s^2 \rangle}{1/4 D_s^2 + \langle d_s^2 \rangle}$$

where $\langle \quad \rangle$ symbolizes the average over the n_s -distribution.

To prove this identity, one uses the fact that

$$b = \frac{\text{cov}(n_F, n_B)}{\text{var } n_F} = \frac{\sum_i (n_F(i) - \bar{n}_F) (n_B(i) - \bar{n}_B)}{\sum_i (n_F(i) - \bar{n}_F)^2}$$

(where the sums are over all events (i)) and one carries out the sums in two steps; first for events with $n_F(i) + n_B(i) = n_s$ fixed, second over n_s .

One finds that if the observed particles were emitted (for fixed n_s) with constant probability into F or B the distribution, $f(n_F | n_s)$ would be binomial and $d_s^2(n_F) = 1/4 n_s$. In this case

$$b = \frac{D_s^2 - \bar{n}_s}{D_s^2 + \bar{n}_s}$$

A second remark is that if the total n_s -distribution was Poissonian, then $D_s^2 = \bar{n}_s$ and $b = 0$ would follow. However, the n_s -distribution is not a Poisson. It is much broader, and one has

approximately $D_s \approx w \cdot \bar{n}_s$. This goes in the right direction to produce a positive value of the correlation strength parameter b and to give $b \rightarrow 1$ as the limit at very high energies. However, inserting the observed values for the case $0 < |\eta| < 4$, which are $D_s = 8.8 \pm 0.1$ and $n_s = 16.0 \pm 0.2$, gives much too high a value for b ($b = 0.66$). The remedy for this discrepancy is to invoke the fact that particles are emitted together in clusters. As a side remark we note that energy-momentum conservation could lead to emission in opposite directions. However, since we have unobserved leading particles and furthermore observe only a restricted range in pseudorapidity, the effect of energy-momentum conservation is not strong. Let us, therefore, return to consider clusters. The relation between the number of clusters, (C) , their sizes (k_i) and the observed particles (n) , is

$$n = \sum_{i=1}^C k_i$$

Generally, both C and k_i fluctuate around their mean values $(\bar{C}, \bar{k})$. As an illustration of the way clusters remedy the discrepancy, we ignore the fluctuation in the sizes and take all k_i equal, i.e. $n_s = k \cdot C_s$ where C_s and n_s fluctuate but k is fixed. Then $d^2 = 1/4 k^2 \cdot C_s = 1/4 k \cdot n_s$ based on the assumptions that the number of clusters falling into F (or B) is governed by the binomial distribution, and that all k particles from a cluster remain in the same η -interval as the parent cluster. Then

$$b = \frac{D_s^2 - k \bar{n}_s}{D_s^2 + k \bar{n}_s}$$

One finds that $k \approx 2$ is needed to yield the observed b ($=0.41$). In a more realistic model the cluster sizes fluctuate. Under the same conditions as above it can be shown⁴⁸ that the relation given is changed into

$$b = \frac{D_s^2 - k_{\text{eff}} \bar{n}_s}{D_s^2 + k_{\text{eff}} \bar{n}_s}$$

Here $k_{\text{eff}} = \bar{k} + d_k^2/\bar{k}$, where (k, d_k^2) are the first two moments of

Fig. 18 The variance d^2 of the n_F distribution at fixed total multiplicity n_s as a function of n_s for three selected regions of pseudorapidity η . The curves are obtained from two Monte Carlo simulations with assumed average cluster sizes of 2 and 3 charged particles, respectively.

the cluster decay distribution. There is one more fluctuation to consider. The decay products (k_i particles) of a given cluster may leak out from or into the chosen rapidity interval. Monte Carlo studies show that this effect lowers the effective k in the relation above. In Fig. 18 the quantity $4d_s^2/n_s$ is plotted vs $n_s = (n_F + n_B)$. In the oversimplified case of single particle binomial distribution at fixed n_s , this quantity is expected to be 1, whereas binomially distributed clusters of fixed size k should lead to a value equal to k . Data points are compared to a simple Monte Carlo simulation. In each event with a given number of clusters (C), the C positions in pseudorapidity (η) are chosen at random such as to reproduce the η -distribution after cluster decay (gaussian with a width as observed in the study of short range correlations). The distributions

of C is taken so as to reproduce the observed charge particle multiplicities. For this program one has to assume the properties of the cluster decay distribution. It turns out that $\bar{k} \sim 2$ and $d_k^2/\bar{k} \sim 0.6$ (truncated Poisson) gives a good description of the data. The same parameters account for the short range correlation. Fig. 19 shows some examples (of many) of $f(n_F|n_S)$ distributions based on the simple cluster Monte Carlo simulation with cluster sizes fluctuating around an average of $\bar{k} = 2$.⁴⁷ The agreement with data is good. Data are not reproduced if particles rather than clusters are binomially distributed, nor if clusters of fixed size are assumed.

Fig. 19 Distributions of n_F at fixed total multiplicity n_S , i.e. $P(n_F/n_S)$ for $n_S = 13, 14, 15$ and 16 charged particles respectively. The Monte Carlo simulation carried out with an average cluster size of 2 charged particles and assuming binomial distribution of clusters into each hemisphere (at fixed number of clusters) (UA5 unpublished).

The conclusion is that the clusters are small (~ 2 charged particles). High multiplicity events would thus correspond to the production of many small clusters rather than a few large clusters. However, the statistics in the extreme high multiplicity tail prevents one making valid conclusions over the full range of multiplicities.

Before leaving the subject of long range correlations, I would like to return to the empirical result as given in Fig. 17. One can ask if there is any good reason why the points of average n_B (at fixed n_F) are so close to a straight line. It must reflect some property of the two-dimensional distribution in the scatterplot. Let us idealize to a scatterplot $f(C_F, C_B)$ of clusters (rather than particles), for which we have reasons to believe that $f(C_B|C)$, i.e. at fixed $C = C_F + C_B$ is a binomial distribution and also assume that the linear relation $\langle C_B \rangle = a' + b' \cdot C_F$ is exact. With these two assumptions one can prove mathematically⁴⁰ that the distribution in the sum $C (= C_B + C_F)$ has to be a negative binomial. A corollary is that the projected distributions in C_F and C_B also are negative binomials. One is reminded that this type of discrete distribution (or its asymptotic continuous form) plays a central rôle in two of the above mentioned recent models^{33,34}.

3. RESULTS FOR IDENTIFIED PARTICLES

3.1. Photons, π^0 -, η -Mesons.

Both the UA1 and UA2 experiments can observe photons in the electromagnetic calorimeters. The UA5 group has observed the tracks of electron-positron pairs from γ -rays converted in the beam pipe or in lead converters inserted in the streamer chamber.

The UA2 group⁴¹ has presented clear evidence for both π^0 and η -meson production. Fig. 20 shows the mass distribution for 2γ 's with the two peaks.

Fig. 20 The π^0 and η peaks in the distribution of invariant 2γ -masses (UA2).

The UA5 experiment⁴² has measured the rapidity distribution of photons (γ 's), shown in Fig. 21. The same figure shows the density of charged particles. Obviously there is an excess of photons, whereas one would expect equal numbers if all photons came from π^0 decay and if all charged particles were $\pi^\pm$. Removing the estimated number of $K^\pm$, p , $\bar{p}$ as well as photons from $K_S^0 \rightarrow 2\pi^0 + 4\gamma$, one still is left with a sizeable excess of photons as is seen in Fig. 21b. If this is attributed to η -meson production, the UA5 result is $\eta/\pi^0 \approx 30\%$, whereas UA2 reports $\eta/\pi^0 \approx 50\%$. Results from the ISR⁴³ also show a strong η -production with a ratio of 20%.

Fig. 21 The excess of γ -rays over charged particles as observed in the UA5 experiment. In (a) all data vs the pseudorapidity; in (b) data corrected for other particles than pions and η -mesons.

3.2. Strange Particles.

Results have been reported by the UA2 and UA5 groups. In UA2 the identification of $K^\pm$ is made by the time of flight method⁴⁴. In UA5 information on K_s^0 and $\Lambda/\bar{\Lambda}$ is obtained by a statistical analysis of decay angles⁴⁵. It is a good exercise to find out how this is possible and why it also yields the momentum of the particle.

As is seen in Fig. 22 the UA2 group finds the transverse momentum spectrum of charged K-mesons harder (less steep) than that of π -mesons. They also find the particle ratios to be approximately constant when plotted against the "transverse mass", i.e. $M_T = (M^2 + p_T^2)^{1/2}$. The ratio $K^\pm/\pi^\pm$ has increased from that at ISR energies. The UA5 group finds from the measured p_T distribution,

Fig. 22 The distribution of transverse momenta of charged K-mesons in comparison with pions and protons as measured in the UA2 experiment. Also the particle ratios protons/pions and K-mesons/pions as a function of transverse mass.

Fig. 23, that the average p_T is high, being 0.70 GeV/c for K^0 and 0.65 GeV/c for $\Lambda/\bar{\Lambda}$. Also the production has increased. The ratio $(K^0 + \bar{K}^0)/\pi^\pm = 0.12 (\pm 0.03)$ is reported, to be compared with generally lower values at lower energies, Fig. 24. Also the baryon + antibaryon production has increased from about 5% at ISR to about 9% at SPS Collider. More data are needed on these subjects before we can be sure about these tendencies and relate them to basic processes.

Fig. 23 The distribution of transverse momentum of neutral K_S mesons and $\Lambda/\bar{\Lambda}$ hyperons (UA5 data). Also the pseudorapidity distribution of K-mesons in a limited region of pseudorapidity.

Fig.24 a) The mean transverse momentum of K-mesons.
 b) The K/π ratio at various energies including the UA5 result at 540 GeV for $(|\eta| < 3)$.

3.3. The Average Event.

Compiling what is known about the production of various particles in given rapidity intervals, one tries to extrapolate from $|\eta| < 3$ to $|\eta| < 5$, which is close to full space (same relative increase as for charged particles). In this way $K^\pm$, $(K^0 + \bar{K}^0)$, $(\Lambda + \bar{\Lambda})$ production is found. Furthermore, one can make reasonable extrapolations about particle ratios at lower energies to obtain estimates for $(p + \bar{p})$ and $(n + \bar{n})$ productions based on the observed production of $(\Lambda + \bar{\Lambda})$ hyperons. A proportional amount of Σ 's is assumed ($\sim 50\%$ of Λ^0). The remaining average charged multiplicity is

TABLE

The average particle content of an event at the SPS Collider at 540 GeV as estimated by the UA5 group. Measurements are underlined, inferred values for the pseudorapidity range $-5 < \eta < 5$ are given in the third column (beyond $|\eta| = 5$ one expects very few particles).

Type of particle	540 GeV		53 GeV
	$\langle \eta \rangle$		$\langle \eta \rangle$
	SPS Collider		ISR
	for $ \eta < 3$	for $ \eta < 5$	
All charged	<u>19.5</u>	<u>26.5</u>	10.1
K^+ and K^-	<u>1.8</u>	2.5	<u>0.75</u>
K^0 and $\bar{K}^0$	<u>2.0</u>	2.7	<u>0.7</u>
Λ and $\bar{\Lambda}$	<u>0.35</u>	0.5	0.1
p and $\bar{p}$		1.5	0.3
$\Sigma^\pm$ and $\bar{\Sigma}^\pm$		0.25	0.04
$\pi^\pm$		22.3	9.0
$\bar{n}$ and n		1.5	0.3
all γ		31.5	<u>11.8</u>
η		3.5	1.1
γ from η		11.2	3.4
$\pi^\pm$ from η		2.1	0.6
$\pi^\pm$ (not η)		20.2	8.4
π^0 (not η)		10.1	4.2

assumed to be $\pi^\pm$. Out of a total average of 26.5 charged particles, the charged pions are 22.3 or 84%. The compilation is summarized in the Table (UA5-compilation)⁴⁶, which also shows the estimated η -meson production based on the further assumption that $\pi^0/\pi^\pm = 1/2$, after η -meson decays are eliminated.

The total number of charged particles (tracks) is 26.5 on the average and the number of photons is 31.5. Counting identifiable particles (charged and neutral) gives from the Table an average of 42.7 in the interval $|\eta| < 5$. An extrapolation to full phase space (by Monte Carlo) gives about 44 produced particles on the average, not including 2 leading baryons. One should remember that the particles are produced via small groups of resonances (clusters).

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