CERN/EP 82-179
12 November 1982

Particle multiplicities in $\bar{p}p$ interactions at $\sqrt{s} = 540$ GeV

UA5 Collaboration

Bonn¹, Brussels², Cambridge³, CERN⁴, Stockholm⁵

K. Alpgård⁵, R.E. Ansorge³, B. Åsman⁵, S. Berglund⁵, K. Berkelman^{4*},
D. Bertrand², K. Böckmann¹, C.N. Booth³, C. Buffam⁴, L. Burow¹, P. Carlson⁵,
J.-L. Chevalley⁴, B. Eckart¹, G. Ekspong⁵, I. Evangelou⁴⁺, J.-P. Fabre⁴,
K.A. French³, J. Gaudaen^{2**}, M. Gijsen⁴, K. von Holt¹, R. Hospes¹, D. Johnson²,
K. Jon-And⁵, Th. Kokott¹, R. Mackenzie⁴, M.N. Maggs³, R. Meinke¹, Th. Müller¹,
H. Mulkens⁴, D.J. Munday³, A. Odian^{4#}, M. Rosenberg¹, J.G. Rushbrooke³,
H. Saarikko^{1##}, T. Saarikko¹, F. Triantis⁴⁺, Ch. Walck⁴, C.P. Ward³, D.R. Ward³,
G. Weber⁴⁺⁺, A.R. Weidberg³, T.O. White³, G. Wilquet² and N. Yamdagni⁵.

- 1 Physikalisches Institut der Universität Bonn, Fed. Rep. Germany.
- 2 Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium
- 3 Cavendish Laboratory, Department of Physics, Cambridge University, UK.
- 4 CERN, Geneva, Switzerland
- 5 Institute of Physics, University of Stockholm, Sweden

ABSTRACT

We present the charged multiplicity distribution in $\bar{p}p$ interactions at $\sqrt{s} = 540$ GeV. Moments of the distribution are given, and compared with KNO scaling predictions. An estimate of the particle composition at collider energies is also made.

Submitted to Physics Letters B

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- *) Visiting scientist from Cornell University, Ithaca, NY, USA
 - **) Also at the Universitaire Instelling Antwerpen, Antwerp, Belgium
 - *) Visiting scientist from SLAC, Stanford, Calif., USA
 - ##) Visiting scientist from Helsinki University, Finland
 - +) Visiting scientist from Ioannina University, Greece
 - ++) Visiting scientist from Hamburg University and DESY, Hamburg, Fed. Rep. Germany.

Introduction

The purpose of this paper is to report on a detailed study of particle multiplicities in $p\bar{p}$ interactions at $\sqrt{s} = 540$ GeV. The data were obtained using the UA5 streamer chamber detector at the CERN SPS collider. This detector is well suited to a study of the charged multiplicity distribution, since it covers a large region of pseudorapidity ($\eta = -\log \tan \theta/2$) with good resolution. This range of pseudorapidity, $|\eta| < 5$, contains $\sim 93\%$ of charged particles produced.

We have presented earlier results on the charged multiplicity distribution [1], based on ~ 300 interactions. We are now able to make a more detailed study of the shape of the distribution, using ~ 4500 completely measured and reconstructed events. This number of events corresponds roughly to the statistical level at which systematic uncertainties start to exceed the statistical errors.

We shall investigate the energy dependence of the charged multiplicity distribution. The SPS collider offers important advantages in such a study, since it provides almost a tenfold increase in the c.m. energy and a doubling of the average multiplicity compared with the CERN ISR. Approximate KNO scaling has been observed at c.m. energies $\sqrt{s}$ from ~ 12 to ~ 63 GeV, and our data may help to clarify whether this scaling represents the onset of asymptopia, or whether perhaps the energy range previously available was simply insufficient to observe violations of KNO scaling.

We also summarize the multiplicities of different particle types produced in a "typical event" at $\sqrt{s} = 540$ GeV. In particular we can estimate the proportions of kaons and baryons/antibaryons produced and compare these with previous data from the ISR.

Experimental Details

The UA5 detector and standard analysis procedures have been described in previous publications [1,2,3]. Two large streamer chambers, $6\text{m} \times 1.25\text{m} \times 0.5\text{m}$, were placed above and below the SPS beam pipe, giving a geometrical acceptance of $\sim 95\%$ for $|\eta| \lesssim 3$, falling to zero at $|\eta| \approx 5$. The trigger for the chambers was provided by four large scintillation counter hodoscopes [3]. This trigger rejected essentially all elastic and single diffractive events, but accepted $96 \pm 2\%$ of non single-diffractive events as determined by Monte-Carlo simulations. The streamer chamber tracks were photographed by six cameras, and these tracks were measured, geometrically reconstructed and associated with primary or secondary vertices as explained in ref [3]. In view of the low luminosity of the machine when these data were taken the probability that a high multiplicity event could arise from an accidental coincidence of two events is negligibly small, $\sim 10^{-5}$. The results presented below are based on a sample of 4442 events.

A Monte-Carlo simulation was used to correct the data for trigger losses of non-single diffractive events, geometrical acceptance, and residual contamination of primary tracks by secondaries (e.g. e^+e^- pairs or strange particle decay products). Simulated events were tracked through the detector allowing for interactions and scattering. Simulated measured events were thereby produced which were then processed in the same way as real measurements. The event generators in the Monte-Carlo program were adjusted so as correctly to reproduce the observed rapidity distributions as a function of charged multiplicity [1], and the observed yields of kaons [4] and photons [5] as a function of charged multiplicity.

Correction of the charged multiplicity distribution

The observed charged particle multiplicity distribution before correction is presented in fig 1(a). Monte-Carlo studies show that the observed multiplicity is on average $\sim 80\%$ of the true charged multiplicity in the full phase space, as shown in the inset to fig 1(a). The Monte-Carlo simulation shows that $\sim 7\%$ of all charged particles are produced in the region $|\eta| > 5$ where our acceptance is zero. From our Monte-Carlo simulation we can compute P_{mn} , the probability of a true triggered n -prong event being observed to have m tracks and also ϵ_n , the trigger efficiency for n -prong events. If O_m is the number of events observed to have m tracks, and T_n is the true number of n -prongs we then have:

$$O_m = \sum_n P_{mn} T_n \epsilon_n . \quad (1)$$

This is an overconstrained set of linear equations because n is even whereas m may be even or odd. A solution for T_n may be obtained using standard least-squares techniques or by an iterative method. In practice in order to obtain a stable solution it was necessary to impose a smoothness constraint on the corrected distribution T_n .

The corrected non single-diffractive multiplicity distribution is shown in fig 1(b). It should be noted that the corrected distribution has strong correlations between neighbouring values of n_{ch} because events of any given observed multiplicity may originate from several adjacent values of true multiplicity, and also because of the smoothness constraint. Because of these correlations it is misleading to draw the errors in fig 1(b) corresponding to the diagonal terms of the covariance matrix, and we have therefore chosen to represent them by $\sqrt{T_n}$.

It is a straightforward matter to compute the moments of the multiplicity distribution using the full covariance matrix of T_n (table 1). The average charged multiplicity is found to be 28.9 ± 0.4 . As stated in our earlier publication [1] after making a plausible correction for the single diffractive component this value is consistent with the the best fit to the energy dependence of lower energy data [6], a quadratic in $\log s$, but is not consistent with the form $s^{\frac{1}{4}}$ favoured by statistical or hydrodynamical models (e.g. ref. [7]). An explicit prediction for $\langle n_{ch} \rangle$ in non-diffractive pp interactions is made in ref. [8], based on single quark and diquark jet multiplicities. The value obtained, 29.4, is in good agreement with our measurement.

Energy dependence of multiplicity distributions

The KNO scaling law [9]:

$$\langle n \rangle \frac{\sigma_n}{\sum \sigma_n} \xrightarrow{s \rightarrow \infty} \phi(z = n/\langle n \rangle)$$

was originally derived assuming Feynman scaling in the very high energy limit. Although this assumption is now known not to be valid, particularly near $\eta=0$ [3,6,10] it appears that pp multiplicity distributions obey KNO scaling to a reasonable approximation at energies between $\sqrt{s} \sim 12$ and 63 GeV [6,11]. Analysis of the moments of multiplicity distributions suggests that $z' = (n-\alpha)/(\langle n \rangle - \alpha)$ with $\alpha \sim 1$ may be a better scaling variable [6,12]. KNO scaling may therefore provide a useful phenomenological framework on which to base comparisons of our results with lower energy data

A fit to $\phi(z)$ has been made by Slattery [11] using data up to $\sqrt{s} = 27$ GeV. A theoretical prediction of $\phi(z)$, due to de Groot [13], was slightly favoured at the ISR [6]. The KNO scaling prediction based on the

Slattery fit using our observed $\langle n \rangle = 28.9$ is shown as the dashed curve in figs 1(a) and 1(b). In fig 1(a) the KNO prediction was convolved with the acceptance matrix P_{mn} . It is easier to make a comparison using fig 1(a), since the data points are uncorrelated. We see that the Slattery function does not give a good description of the shape ($\chi^2 = 185$ for 75d.f.) and shows evidence for systematic discrepancies. In the case of the de Groot function (not shown) the high multiplicity region is better fitted, but elsewhere the agreement is no better (overall $\chi^2 = 172$ for 75 d.f.).

However, our data exclude single diffractive events (presumably of comparatively low multiplicity) whilst the data which were described by the Slattery and de Groot functions included such events. At present our best estimate is that single diffraction amounts to $\sim 18\%$ of the inelastic cross-section [14]. One way to allow for the exclusion of single diffractive events from our data is to compare with published data which have single diffraction excluded [15]. We find that these data, in the energy range $\sqrt{s} = 4.9-27$ GeV, are consistent with KNO scaling with

$$\phi_{\text{NSD}} = (-4.11z + 83.68 z^3 - 17.70z^5 + 0.93z^7) e^{-3.55z}$$

If we use ϕ_{NSD} (non single-diffractive) in the KNO scaling prediction with our observed $\langle n \rangle = 28.9$ we obtain a poor fit to our data ($\chi^2 = 338$ for 75 d.f.). In order to obtain a good description of the main peak in our distribution using ϕ_{NSD} it is necessary to take $\langle n \rangle \sim 26$, as shown by the solid curves in fig 1(a,b). In this case, though, the data show a substantial excess over the KNO prediction for the highest multiplicities ($z \gtrsim 1.5-2$).

An alternative way of studying KNO scaling is via the moments of the distribution. For example, in the case of perfect KNO scaling the dispersions, $D_q = \langle (n - \langle n \rangle)^q \rangle^{1/q}$ should be proportional to $\langle n \rangle$. In fig 2 we plot D_2 against $\langle n \rangle$, both for data with single diffraction excluded and included [6,12,15]. The data with single diffraction included lie on a straight line (dashed curve) intersecting the $\langle n \rangle$ -axis at ~ 1 . The higher moments show similar behaviour [6], indicating that ideal KNO scaling is not obeyed, but that a better choice for the KNO scaling variable may be $z' = (n - \alpha) / (\langle n \rangle - \alpha)$ with $\alpha \approx 1$. An extrapolation of this line is consistent with our result, but because of the exclusion of single diffraction from our data this agreement is probably fortuitous. The lower energy non single-diffractive data in fig 2 are compatible with a straight line passing through the origin (solid curve), i.e. ideal KNO scaling. However, our data point lies well away from this line, indicating a significant violation of KNO scaling for the non single-diffractive component of the cross-section, probably associated with an increasing proportion of high multiplicity events.

Another possible interpretation of the data is indicated by the dotted curve in fig 2, namely KNO scaling in the variable $z' = (n - \alpha) / (\langle n \rangle - \alpha)$ with $\alpha \sim 2$. This line is consistent with the UA5 measurement and most of the other data, except for the lowest energy data points. This might be accounted for by threshold effects or possible systematic errors in the data of ref.[15] arising from experimental uncertainties in identifying diffractive events. However, we have no physical interpretation of the value $\alpha \sim 2$. The higher moments lead to conclusions entirely consistent with those drawn from D_2 . In table 1(b) we give moments extrapolated to collider energies following each of the above prescriptions.

Particle composition at $\sqrt{s} = 540$ GeV

Using the UA5 detector we have measured the yields of charged particles [3,5] and photons [5] in the region $|\eta| < 5$, and $K^\pm$, K_S^0 , Λ and $\bar{\Lambda}$ in the region $|\eta| < 3$ [4]. Using these results, together with some plausible assumptions, we can estimate the particle composition in $p\bar{p}$ interactions at $\sqrt{s} = 540$ GeV. We shall not consider here the region $|\eta| > 5$ where our detection efficiency is zero; our Monte-Carlo simulation suggests that there will be typically ~ 3 particles/event in this region, normally including one leading baryon and one leading antibaryon, and the analysis may therefore be taken to be representative of the production of non-leading particles (note that $\eta \sim 5$ corresponds to a value of the Feynman scaling variable $x \sim .11$ for $p_T \sim 0.4$ GeV/c).

The assumptions we make are as follows:

- i) The yields of kaons and $\Lambda/\bar{\Lambda}$ can be extrapolated from $|\eta| < 3$ to $|\eta| < 5$ using the observed yields of all charged particles (table 2) assuming that all these particles have roughly the same form of rapidity distributions, i.e. multiplying by $\langle n_{ch}(|\eta| < 5) \rangle / \langle n_{ch}(|\eta| < 3) \rangle = 26.5/19.5$.
- ii) The ratio $\sigma(\bar{p})/\sigma(\bar{\Lambda})$ is taken to be 3. The region $|\eta| < 5$ will largely exclude baryons coming from beam fragmentation, so it is appropriate to examine lower energy pp data on $\bar{p}$ and $\bar{\Lambda}$ production to estimate the production of central baryon-antibaryon pairs. Fig 3 shows the existing, though rather sparse, data [16,17], which are compatible with this assumption.
- iii) We assume $\sigma(\Lambda) = \sigma(\Sigma^+ + \Sigma^- + \Sigma^0)$. The Σ^0 contribution is as usual included in the Λ yield.

iv) We assume $\sigma(n+\bar{n}) = \sigma(p+\bar{p})$.

Using these assumptions the upper part of table 2 has been completed.

The main source of photons is expected to be π^0 decays. However, in ref [5] we observed an excess of photons over $\pi^\pm$, and surmised that this excess might be caused by η -meson production. Further evidence of copious η meson production, albeit at $p_T \gtrsim 1.4$ GeV/c, has come from the UA2 experiment [18]. If this is accepted as the most plausible source of the photon excess the lower part of table 2 giving pion and η meson yields may be derived. In table 2 we also show for comparison, corresponding particle yields at $\sqrt{s} = 53$ GeV using ISR data on $\bar{p}, \pi^\pm$ and $K^\pm$ production [17] and photon production [19], applying the same assumptions detailed above, and excluding leading baryons.

We conclude that a typical event at $\sqrt{s} = 540$ GeV has ~ 43 primary stable particles produced in $|\eta| < 5$, obtained by summing those marked with an asterisk * in table 2. Of these $\sim 12\%$ are kaons and $\sim 9\%$ baryons or antibaryons. For comparison the corresponding figures at $\sqrt{s} = 53$ GeV are 9% and 5%. We thus infer an increase in the proportions of kaons and baryons produced at the SPS collider as compared with ISR energies. These results take no account of the effect of strongly decaying resonances; in view of the observed similarity of correlation phenomena at SPS and ISR [20] we may guess that the proportion of particles originating from resonance decays has not altered too much.

Summary

In this study of particle multiplicities at $\sqrt{s} = 540$ GeV we have drawn the following conclusions:

- i) The corrected multiplicity distribution has been derived. The average charged multiplicity, 28.9 ± 0.4 , is consistent with a quadratic dependence on $\log s$, after allowing for single diffractive dissociation, but excludes stronger forms of energy dependence such as $s^{\frac{1}{4}}$.
- ii) We have used the framework of KNO scaling to compare the shape of the multiplicity distribution with lower energy data. If we use lower energy data which include single-diffractive events we find some violations of KNO scaling. However, since our SPS data exclude single diffraction agreement is probably not to be expected. If we use published data which exclude single diffraction we observe a clear violation of KNO scaling, with a greater proportion of high multiplicity events at $\sqrt{s} = 540$ GeV. It is possible that the non-diffractive data could be consistent with KNO scaling in the variable $z' = (n - \alpha) / (\langle n \rangle - \alpha)$ with $\alpha \sim 2$.
- iii) Making some plausible assumptions we estimate that the primary stable particles produced contain $\sim 12\%$ kaons and $\sim 9\%$ baryons and antibaryons. These fractions represent an increase from ISR energies.

Acknowledgements

We are indebted to the many members of the CERN staff, particularly from the SPS and EF Divisions, who have contributed to the success of the SPS Collider and of our experiment. From the Brussels group, thanks are due from D.B and G.W. for the financial support of the Fonds National de la Recherche Scientifique and the Institut Interuniversitaire des Sciences Nucléaires, and from J.G and D.J. to the Interuniversitaire Institut voor Kern Wetenschappen for financial support. We also acknowledge with thanks the financial support of the Bonn group by the Bundesministerium für Wissenschaft und Forschung, of the Cambridge group by the UK Science and Engineering Research Council, and of the Stockholm group by the Swedish Natural Science Research Council. Last, but not least, we acknowledge the contribution of the engineers, scanning and measuring staff of all our laboratories.

Table 1(a) Moments of corrected charged multiplicity distribution at $\sqrt{s} = 540$ GeV

$\langle n \rangle$	28.9 ± 0.4
D_2	15.4 ± 0.3
D_3	15.5 ± 0.5
D_4	21.7 ± 0.6
$\langle n \rangle / D_2$	1.88 ± 0.03
C_2	1.28 ± 0.01
C_3	2.00 ± 0.04
C_4	3.61 ± 0.13
γ_2	$.282 \pm .009$
γ_3	$.152 \pm .015$
γ_4	$.075 \pm .020$

The errors quoted are purely statistical. We estimate that the systematic errors are of a similar order of magnitude.

The dispersions D_q are defined by $D_q = \langle (n - \langle n \rangle)^q \rangle^{1/q}$.

The C-moments are defined by $C_q = \langle n^q \rangle / \langle n \rangle^q$.

The γ -moments are defined by $\gamma_2 = (D_2 / \langle n \rangle)^2$;

$\gamma_3 = (D_3 / \langle n \rangle)^3$; $\gamma_4 = (D_4^4 - D_2^4) / \langle n \rangle^4$.

Table 1(b) Extrapolation of D moments to $\langle n \rangle = 28.9$ assuming
that $D_q \propto (\langle n \rangle - \alpha)$

	D_2	D_3	D_4
Measured values at $\sqrt{s} = 540 \text{ GeV}$	15.4 ± 0.3	15.5 ± 0.5	21.7 ± 0.6
Extrapolate inclusive data; $\alpha \sim 1$ [6]	16.1 ± 0.4	14.6 ± 0.4	22.2 ± 0.4
Non-single-diffractive data; $\alpha = 0$	13.1 ± 0.4	11.6 ± 0.4	17.3 ± 0.4
Non-single diffractive data; $\alpha \sim 2$	15.4 ± 0.4	14.6 ± 0.4	21.4 ± 0.4

Table 2 Average particle multiplicities at SPS collider and ISR. The SPS data refer to $|\eta| < 5$, and thus exclude leading particles, whilst in the ISR data we have excluded leading baryons (defined as the difference between p and $\bar{p}$ etc.)

Particle type	SPS Collider; $\sqrt{s} = 540$ GeV		ISR $\langle n \rangle$ $\sqrt{s} = 53$ GeV
	$\langle n \rangle$ for $ \eta < 3$	$\langle n \rangle$ for $ \eta < 5$	
All charged	<u>19.5</u>	<u>26.5</u>	10.1
$K^\pm$	<u>1.8</u>	2.5 *	<u>.75</u> *
$p + \bar{p}$		1.5 *	<u>.3</u> *
$\Sigma^\pm + \bar{\Sigma}^\pm$		.25 *	.04 *
$\pi^\pm$		22.3	<u>9.0</u>
$\Lambda + \bar{\Lambda}$	<u>.35</u>	.5 *	.1 *
$K^0 + \bar{K}^0$	<u>2.0</u>	2.7 *	<u>.7</u> *
$n + \bar{n}$		1.5 *	.3 *
All γ		<u>31.5</u>	<u>11.8</u>
η		3.5 *	1.1 *
γ (from η)		11.2	3.4
$\pi^\pm$ (from η)		2.1	.6
$\pi^\pm$ (not from η)		20.2 *	8.4 *
π^0 (not from η)		10.1 *	4.2 *

The items underlined are directly measured. The other values have been estimated following the assumptions in the text. The items marked with an asterisk are the long lived particles produced in the primary interaction, including the products of strong decays.

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Figure Captions

- 1(a) The distribution of observed charged multiplicities in the UA5 experiment. The dashed curve is the KNO scaling prediction based on Slattery's fit to $\phi(z)$. The solid curve is based on our own fit to ϕ_{NSD} for non single-diffractive data.
- Inset Average observed charged multiplicity as a function of true multiplicity, as estimated from a Monte-Carlo simulation.
- 1(b) The fully corrected multiplicity distribution at $\sqrt{s} = 540$ GeV. The curves have the same meaning as in fig 1(a).
- 2 Plot of D_2 against $\langle n \rangle$ for inclusive non-single-diffractive data. The lines represent KNO scaling fits to the lower energy data as described in the text.
- 3 Average yields of $\bar{p}$ and $\bar{\Lambda}$ in pp interactions as a function of $\sqrt{s}$. The hand drawn curves show that the $\bar{p}/\bar{\Lambda}$ ratio is consistent with ~ 3 over a wide range of energies.

FIG.1

FIG.2

FIG. 3