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Collaboration-Bonn-Brussels-Cambridge-CERN-Stockholm
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RESULTS FROM THE UA5 EXPERIMENT

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Abstract. - Results are presented from the UA5 experiment at the CERN pp collider with a c.m. energy $\sqrt{s} = 540$ GeV. Charged particle pseudorapidity and multiplicity distributions are presented. Results on short and long range correlations are given. The production of strange particles and photons has been measured and a search has been made for the so called Centauro phenomenon.

1. Introduction and experimental details

This paper summarizes the results obtained by the UA5 experiment at the CERN pp collider. At the time of this presentation it is less than a year since the collider made its first successful operation, extending the attainable accelerator energy range from about $E_{\text{c.m.}} = 60$ GeV (CERN-ISR) to $E_{\text{c.m.}} = 540$ GeV at the collider.

The aim of the UA5 experiment was to make a rapid survey of hadronic interactions in this new energy regime and, in particular, to look for new phenomena. To meet our requirements of high multiparticle detection efficiency and large solid angle coverage a visual detector consisting of two large streamer chambers was chosen. The set-up is shown in Fig. 1. A detailed description of the detector has been given in Ref. [1] and only the main apparatus will be summarized here.

The streamer chambers, each of size $6 \times 1.25 \times 0.5$ m$^3$, were placed 9 cm apart, above and below the beam axis at the collider. The chambers were triggered by a set of scintillation counter hodoscopes [1,2] and were photographed each by three cameras (demagnification 1/50 and 1/80). The spatial resolution obtained after track reconstruction was about 2 mm.

The beam pipe made of 0.4 mm thick corrugated steel was of elliptical cross-section $60 \times 150$ mm$^2$. It served also as a photon converter and the electromagnetic showers observed in the chambers were used to estimate the production of photons. Lead glass plates, one radiation length thick, were also fitted inside the chambers to convert photons [3].
Some details of the data taking and analysis procedures are given in section 2. Results on charged particles: rapidity distribution, multiplicity distribution and correlations are given in section 3. Neutral particles are dealt with in section 4; the production of strange particles, of photons, and a general summary of particle production. The search for Centauro phenomena is the subject of section 5 and a summary in section 6 ends the paper.

2. Data taking and analysis

The UA5 detector took data during two short machine development periods in October and November, 1981. The trigger ("Minimum Bias") required a hit in each hodoscope arm (Fig. 1) in coincidence with a bunch-bunch crossing. This trigger excluded single diffraction and elastics, but accepted $96 \pm 3\%$ of remaining inelastic events [2]. The machine luminosity was at best $2 \times 10^{25} \text{cm}^{-2} \text{s}^{-1}$ corresponding to bunches containing approximately $10^9$ antiprotons and $5 \times 10^{10}$ protons. The bunch length was about 0.5 m. The trigger rate was typically 0.5 Hz, of which about 0.15 Hz was pp interactions. A total of 60 000 events were recorded on film of which 16 000 were $p\bar{p}$ interactions.

In the absence of a magnetic field charged primaries produced straight tracks coming from a common vertex. In analyzing these we use the pseudorapidity variable $\eta = -\ln \tan \theta/2$ where $\theta$ is the emission angle with respect to the beams. The geometrical acceptance of the detector was about 95% for $|\eta| < 3$ falling to zero at $|\eta| = 5$. In addition to the charged primaries we also observe

- electromagnetic showers from photon conversions in the beam pipe and in the lead glass plates (electromagnetic and hadronic showers are separated by angle cuts [3])
P. Carlson

- hadronic showers and scatters in the beampipe
- charged and neutral decays in the chamber volume \((K_{\pi 3}, K^0, \Lambda)\).

The analysis procedure was to measure the streamer chamber tracks on stereo views, reconstruct them geometrically and to find the positions of the primary vertex and of any secondary vertices. For details of the analysis procedure the reader is referred to Ref. [2, 4].

A Monte-Carlo simulation was used to correct the data for trigger inefficiency, geometrical acceptance of the data and any residual contamination of primary tracks by secondaries, mostly \(e^+e^-\) pairs from conversions in the beam pipe.

Preliminary results on multiplicity and rapidity distributions, based on about 450 \(pp\) events, were published last year [2, 4]. The results presented at this conference are based on about 3000 reconstructed events. The UA5 detector was also used at the ISR where data was taken on \(pp\) and \(\pi\pi\) interactions at \(\sqrt{s} = 53\) GeV [5].

3. Results on charged particles

Pseudorapidity distribution

Fig. 2 shows pseudorapidity distributions folded about \(\eta = 0\) for collider data compared to the ISR data which was obtained with the same apparatus. The available rapidity range has increased from 4.0 to 6.4 units, i.e. by 60% in going from the ISR to the collider, but the width of the distributions at half height has increased only slightly, from 3.2 to 3.9 units (22%). The general rise of the plateau with energy, already observed over the ISR energy range [6], has continued to the collider.

![Pseudorapidity distribution](image-url)

**Fig. 2** Pseudorapidity distribution of charged particles at the collider \(\sqrt{s} = 540\) GeV (open circles) and at the ISR \(\sqrt{s} = 53\) GeV, filled triangles). Errors drawn are statistical only.
The particle density at \( q = 0 \) is \( 3.1 \pm 0.1 \) and this is compared to data at lower energies \([7]\) in Fig. 3. A simple \( \ln s \) extrapolation from the ISR data suggests a density at the collider energy of about 2.7. Correcting for \( (18 \pm 5)\% \) single diffraction \([8]\), an event type presumably not contributing significantly to the density at \( q = 0 \), we get a value of 2.5, compatible with the extrapolation.

The uncorrected multiplicity distribution is shown in Fig. 4. Although the original KNO scaling law \([9]\) was derived using Feynman scaling, which is now known not to hold, pp multiplicity distributions seem to obey KNO scaling between \( \sqrt{s} = 12 \) and 63 GeV \([6, 10]\). It is therefore of interest to test whether our multiplicity distribution at \( \sqrt{s} = 540 \) GeV obeys the KNO scaling. Since our data do not include single diffractive events we have compared our data with published data with single diffraction excluded \([11]\) in the energy range \( \sqrt{s} = 5-27 \) GeV. These data obey the KNO scaling using a parametrization slightly different from that derived \([12]\) for events including single diffraction. Using the non single diffractive parametrization scaled to the collider energy and convolved with the acceptance we get the curve shown in Fig. 4. There is a substantial excess over the KNO prediction for \( n_{\text{ch}} > 40 \). A structure for higher multiplicities has also been reported by the UA5 collaboration to this conference \([13]\).

The charged particle rapidity at \( \eta = 0 \) as a function of \( s \). Open circles are from the UA5 experiment at the collider and at the ISR. Filled circles are from other experiments \([7]\). Errors shown are statistical only, and one should be aware of the different systematic errors. The UA5 point including single diffraction was obtained assuming \( 18 \pm 5\% \) single diffraction (see text).

The distribution of observed charged multiplicities in the UA5 experiment. Errors shown are statistical. The curve is a fit to lower energy data and scaled to \( \sqrt{s} = 540 \) GeV (see text).
The multiplicity distribution can be further studied using its moments and in Fig. 5 we show for non single diffractive data the dispersions $D_q = \langle (n - \langle n \rangle)^q \rangle^{1/q}$ as a function of $\langle n \rangle$, the average multiplicity which from the corrected distribution is estimated to be $\langle n \rangle = 28.9 \pm 0.4$ at the collider [14]. KNO scaling with $n/\langle n \rangle$ as scaling variable would imply that the dispersions $D_q$ should be proportional to $\langle n \rangle$, which is clearly not consistent with the data. The question of scaling in a variable $Z' = (n - \alpha)/(\langle n \rangle - \alpha)$ with $\alpha = 1$ or 2 is discussed in a detailed paper on the multiplicity distribution and its moments [14].

The first moment, the average multiplicity $\langle n \rangle$, is shown as a function of $\ln s$ in Fig. 6. Correcting our measured value $\langle n \rangle = 28.9 \pm 0.4$ for single diffraction [15], it falls nicely on the log$_2 s$ fit obtained by Thomé et al [6] for the data up to ISR energy. A fit of the form $A s^{0.25}$ as proposed by statistical or hydrodynamical models [16] are clearly inconsistent with the data.
We have analyzed our data in terms of short and long range correlations. The short range clustering effect is shown in Fig. 7 where the two particle correlation function $C_{n}^{2}$ is shown as a function of the pseudorapidity difference $\eta_{1} - \eta_{2}$ in a sample of events with total observed multiplicities in the range 20-30. Other multiplicity ranges show very similar behaviour. Neither the height nor the width of about two units has changed significantly in going from the ISR energy [18] to the collider.

Fig. 8a shows a scatterplot of the multiplicities $n_{F}$ and $n_{B}$ observed in the two symmetric pseudorapidity intervals $F = (0 < \eta < 4)$ and $B = (-4 < \eta < 0)$. It is evident from the accumulation of events near the diagonal $n_{B} = n_{F}$ that the multiplicities in the two hemispheres are strongly correlated. This is also shown in Fig. 8b where the average value of the backward multiplicity $\langle n_{B}(n_{F}) \rangle$ at fixed forward multiplicity $n_{F}$ seems to be a linear function of $n_{F}$:

$$\langle n_{B}(n_{F}) \rangle = a + b \cdot n_{F}$$

The slope is a measure of the correlation strength. Our fitted value for the data in Fig. 8 is $b = 0.53 \pm 0.02$. If we introduce a gap of $-1 < \eta < 1$ between the forward-backward region in order to reduce the effect of the short range clustering, the strong correlation remains and the slope attains a value of $b = 0.40 \pm 0.02$.

The correlation parameter $b$ can be expressed in terms of two other quantities closely related to the particle production mechanism, namely the dispersion of the total multiplicity distribution and the dispersion of $n_{F}$ or $n_{B}$ at fixed total multiplicity $n_{S} = n_{F} + n_{B}$ in the pseudorapidity ranges considered. The dispersions observed at fixed $n_{S}$ are too large to be understood if one assumes independent emission of tracks according to a binomial distribution with equal probabilities to fall in the forward or backward regions. Instead we have to assume independent emission of clusters that in turn decay into $k$ charged particles. The dispersions observed are consistent with a cluster size of not more than two charged particles.

This observed cluster size suggests dominance of resonance production ($\rho, \omega, K^{*}, \ldots$) and, as a consequence, that photons should be observed to occur roughly proportionally to charged particles. This is indeed observed in our data (see section 4). A detailed paper on the correlations is being prepared by the collaboration [17].
Fig. 9 The measured $p_T$ distribution for $K^0_S$ and $\Lambda$s. The straight line represents data for $K^0_S$ at $s = 28$ GeV [20].

4. Results on neutral particle production

Strange particles

The inclusive production of $K$s and $\Lambda$s have been measured in the UA5 experiment by observing, in the sensitive volume of the streamer chambers, two-prong neutral decays and one- or three-prong charged decays. The results presented here refer to the pseudorapidity range $|\eta| < 3$ since the probability for observing decays with $|\eta| > 3$ within the chamber volume is very small. A detailed account of the experimental procedures to classify the different decay types as well as of the results on strange particle production has now been published [19].

In Fig. 9 we show the $p_T$ distribution for $K^0_S$ and $\Lambda$. A comparison with $K^0_S$ data at $\sqrt{s} = 28$ GeV [20] (dashed line) suggests that the average $p_T$ has increased at the collider. Fitting an exponential of the form $\exp(-\lambda p_T)$ gives values of the average transverse momentum $\langle p_T \rangle$ of $0.70 \pm 0.12$ GeV/c for $K^0_S$ and $0.65 \pm 0.20$ GeV/c for $\Lambda$. These results are consistent with those presented by the UA2 collaboration at this conference [21]. The observed and corrected number of decays are given in Table 1.
ratios as a function of $s$. Our results for the yields $u$ of different K-mesons are consistent with the relation $K$ which also is a check on our measured value of $\langle p_T \rangle$ for K's, since a larger value of $\langle p_T \rangle$ would increase the number of observed $K_0^*$ but decrease the number of observed $K_0^*$ and $T$.

Our measured value of $\langle p_T \rangle$ is compared to lower energy data [11, 22] in Fig. 10a. Our measured value suggests a significant increase in $\langle p_T \rangle$ at the collider.

The corrected numbers per event were calculated assuming an exponential distribution in $p_T$, at all $p_T$, with a slope for $K$'s equal that measured for $K_S^0$ and for $A$'s equal that measured.

Table 1. Strange particle yields

| Decay type | No. of decays observed in $|\eta| < 3$ | Corrected $^a$ no. of produced particles per event in $|\eta| < 3$ |
|------------|-------------------------------------|---------------------------------------------------|
| $K_S^0 \to 2$ ch. | 22 | 1.0 ± 0.2 |
| $K_L^0 \to 2$ ch. | 17 | 1.0 ± 0.3 |
| $K^\pm \to 3$ ch. | 7 | 1.8 ± 0.2 |
| $\to 1$ ch. | 123 | |
| $A/A \to 2$ ch. | 46 | 0.35 ± 0.10 |

$^a)$ The corrected numbers per event were calculated assuming an exponential distribution in $p_T$, at all $p_T$, with a slope for $K$'s equal that measured for $K_S^0$ and for $A$'s equal that measured.

![Fig. 10](image-url) The average $p_T$ (a) and the $K^0/\pi^+$ and $K^\pm/\pi^\pm$ ratios as a function of $s$ [11, 22, 23].

Our results for the yields $\sigma_K$ of different K-mesons are consistent with the relation

$$\sigma_K = \frac{1}{2} \sigma_{K_S^0} \frac{1}{2} \sigma_{K_L^0} \sigma_{K^\pm}$$

which also is a check on our measured value of $\langle p_T \rangle$ for K's, since a larger value of $\langle p_T \rangle$ would increase the number of observed $K_S^0$ but decrease the number of observed $K_L^0$ and $K^\pm$. Our measured value of $\langle p_T \rangle$ is compared to lower energy data [11, 22] in Fig. 10a. Our measured value suggests a significant increase in $\langle p_T \rangle$ at the collider.

The $K^0/\pi^+$ ratio obtained for $|\eta| < 3$ is $11 \pm 2\%$. This ratio is compared to lower energy data [11, 22, 23] for the $K^0/\pi^+$ and $K^\pm/\pi^\pm$ ratio in Fig. 10b. With the exception of one of the ISR results there is a continuous increase in this ratio. Our measured value is consistent with that on the $K^\pm/\pi^\pm$ ratio presented by the UA2 collaboration at this conference [21].

**Photons**

The inclusive production of photons has been measured in the UA5 experiment by observing the secondary electromagnetic showers from conversions in the beam pipe (for the full $\eta$ range) and in a lead glass plate inserted into the streamer chamber [for a restricted range $|\eta| < 1$]. The method to select photons is described in detail in Ref. [3] which also contains the results presented here.

The corrected pseudorapidity distribution for photons, folded about $\eta = 0$, is shown in Fig. 11 together with that for charged particles based on the same event sample. Integrating the range $|\eta| < 5$ we obtain a significant photon excess: $n_p = 34 \pm 2$ compared to $n_{ch} = 26.5 \pm 1$. The excess (30\%) is concentrated to the range $|\eta| < 2.5$, giving a more narrow shape to the photon distribution.
To compare the production of charged and neutral π's we subtract from the measured pseudorapidity distributions the contributions from K's and protons: $K^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ from the photon distribution and $K^\pm$, $p^\pm$ from the charged particle distribution [24]. The result of the subtractions is shown in Fig. 12.

Fig. 11 The measured pseudorapidity distribution for photons and for direct production of photons and $\pi^0$, obtained by subtraction from the data in Fig. 11. (See text.)

Integrating the data points in Fig. 12 one gets $n^- = 31.5 \pm 2$ and $n^+ = 22.5 \pm 1$, which is in strong disagreement with the empirical result at lower energies that $n^- = \frac{1}{2} n^+$. A possible interpretation of our data is that the excess of photons is due to the production of $\eta$ mesons, in which case we get $\eta/\pi^0 \approx 30\%$. The solid and dashed lines in Fig. 12 are the results of Monte Carlo simulations assuming either that all photons come from the decay of $\pi^0$ (dashed line) or that the excess is due to $\eta$ production (solid line). Both interpretations describe the data adequately. Measurements at the ISR for $p_T > 3$ GeV/c give $\eta/\pi^0 \sim 30\%$ [25]. At the collider the UA2 experiment reports a value for $p_T > 1.5$ GeV/c of $\eta/\pi^0 \approx 55\%$ in a range of pseudorapidity $|\eta| < 1$ [21].

We have analyzed our data for correlations between charged particle and photon production and Fig. 13a shows the average number of photons $\langle n_\gamma \rangle$ as a function of the number of charged particles. There is a strong correlation and the straight line drawn in the figure is

$$\langle n_\gamma \rangle = (8 \pm 3) + (0.90 \pm 0.08) n_{ch}$$

and represents a fit for $n_{ch} < 50$. Also shown for comparison are the ISR results [26] for $\sqrt{s} = 63$ GeV. The energy dependence of the slope is shown in Fig. 13b [26, 27]. A strong correlation between the number of photons and the number of charged particles is expected in a model where resonance production is dominating, (cf. section 3 on charged particle correlations).
Fig. 13 a) The correlation between the number of photons and the number of charged particles observed in the UA5 experiment compared to lower energy data [26].

b) The correlation slope as a function of energy from different experiments [26, 27].

Particle production, summary
Using our measured values of the following average particle multiplicities

<table>
<thead>
<tr>
<th>Particle</th>
<th>Multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>All charged</td>
<td>26.5</td>
</tr>
<tr>
<td>All photons</td>
<td>31.5</td>
</tr>
<tr>
<td>(K^0_+) ((</td>
<td>\eta</td>
</tr>
<tr>
<td>(K_{-}) ((</td>
<td>\eta</td>
</tr>
<tr>
<td>(\Lambda/\Lambda) ((</td>
<td>\eta</td>
</tr>
</tbody>
</table>

and scaling those measured for \(|\eta| < 3\) to \(|\eta| < 5\) by the corresponding charged particle multiplicities and further assuming that the photon excess is due to \(\eta\), that the yield \(n/\bar{n} = p/p = 3 \times \Lambda/\bar{\Lambda} [11]\) and that the yield \(\Lambda = \Sigma^2 + \Sigma^0\), we arrive at the following particle composition at the collider energy \(\sqrt{s} = 540\) GeV.
Table 2. Particle composition as average multiplicity per inelastic, non single diffractive event.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Average multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>20.2</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>10.1</td>
</tr>
<tr>
<td>$\eta$</td>
<td>3.5</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>2.5</td>
</tr>
<tr>
<td>$K^0$</td>
<td>2.7</td>
</tr>
<tr>
<td>$p/\bar{p}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$n/\bar{n}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$\Lambda/\bar{\Lambda}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Sigma^\pm$</td>
<td>0.25</td>
</tr>
<tr>
<td>Total $</td>
<td>\eta</td>
</tr>
</tbody>
</table>

We conclude that, excluding leading baryons, a typical inelastic event at $\sqrt{s} = 540$ GeV has 43 primary particles produced in $|\eta|<5$ of which 12% are kaons and 9% are baryons.

5. Search for Centauro's

One of the aims of the UA5 experiment is to look for new phenomena. Cosmic ray experiments have suggested the existence of an unusual class of hadronic events, called 'Centauros'. These events are characterized [28] by an interaction giving a large number of hadrons but seemingly no photons. From the small number of events observed in the cosmic ray experiments one has estimated the incident laboratory energy to be about 1700 TeV. Although this is well above the corresponding collider energy [equivalent laboratory energy 155 TeV], we have nevertheless examined our high multiplicity events in detail for any resemblance with the Centauro phenomenon. A more detailed account of our Centauro search has now been published [3].

In order to compare our data with the cosmic ray observations we should use similar kinematical conditions and therefore we restrict our search to the regions $\eta>2$ or $\eta<-2$ [3]. As shown in Fig. 14 there is no event in our sample resembling a Centauro and the upper limit for Centauro production is estimated to 1 in 3600 minimum bias events. A significant improvement in the sensitivity of the Centauro search would require a corresponding reduction of the systematic errors, particularly in the classification of tracks as charged primary or secondary electromagnetic shower for $|\eta|>3$. 
6. Summary

The main features of pp hadronic interactions at the collider energy $\sqrt{s} = 540$ GeV as found in the UA5 experiment are:

1) The pseudorapidity density of charged particles at $\eta = 0$ has continued to rise from the ISR energies and attains $dN/d\eta = 3.1 \pm 0.1$

2) The average charged multiplicity of inelastic non-single diffractive interactions is $28.9 \pm 0.4$ and continues to rise with energy like $a + b \ln s + c \ln^2 s$

3) The observed multiplicity distribution suggests a violation of KNO scaling

4) Short range correlations are observed of approximately the same size as at lower energies

5) Strong long range multiplicity correlations are observed and interpreted as independent emission of cluster decaying into about two charged particles. This cluster size suggests dominance of resonance production

6) The production of K mesons is larger than at lower energies with a $K^0/\pi^+$ ratio of $11 \pm 2$

7) The average value of the transverse momenta $p_T$ for $K^0$'s increases with energy

8) There is a substantial excess of photons over charged particles for $|\eta| < 2.5$. This can be interpreted as production of $\eta$ mesons with $\eta/\pi^0 = 30$

9) No evidence has been found for the production of events of Centauro type with an upper limit on the production of 1 in 3600 minimum bias events.

Acknowledgement

I am grateful to my colleagues in the UA5 collaboration for their advice and help.
References

14. K. Alpgård et al.: "Particle multiplicities in pp interactions at $\sqrt{s} = 540$ GeV", to be published.
15. We assume that ($18 \pm 5\%$) of the inelastic events are single diffractive [8] with a charged multiplicity of $n \approx 3$ [12]. We then get $\langle n \rangle = 25 \pm 2$.
24. The subtractions were made assuming that the production of $K^\pm = K^O$ (measured in our experiment) and that the production of $p^\pm = 3 \times A$ \,[12].

25. G. Jansco et al., Nucl. Phys. B124 (1979) 1,
   C. Kourkoamelis et al., Phys. Lett. 84B (1979) 277,


Discussion

E.L. Berger (Argonne).—You conclude that your forward-backward rapidity correlations are explained if you postulate production of clusters with charged multiplicity, $K$, of two. I reached this conclusion in 1973 based on analyses of multi-particle data from the ISR and Fermilab. These clusters explain multiplicity data, rapidity correlations, charged-neutral correlations, and so forth. Details are in my 1973 Erice Lectures, and in a subsequent paper published in Nuclear Physics B, where further tests are proposed. In fact, the mean number of negatives per cluster must be slightly larger than one to account for observed negative-negative correlations. Therefore, $K$ must also be slightly bigger than two (sum of positives and negatives).