A study of the general characteristics of proton-antiproton collisions at
 $\sqrt{s} = 0.2$ to 0.9 TeV.

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ABSTRACT

The general characteristics of inelastic proton-antiproton collisions at the CERN SPS Collider are studied with the UA1 detector using magnetic and calorimetric analysis. Results are presented on charged particle multiplicities and transverse and longitudinal momenta, and on total transverse energy distributions at centre of mass energies ranging from 0.2 to 0.9 TeV.

1. Introduction.

Inclusive charged and neutral particle distributions have been studied for a long time to derive the general features of hadronic collisions at different centre of mass energies. Over the Fermilab fixed target and ISR energy range, proton-proton interactions are characterized by an increase of both the multiplicity density in the central region and the total multiplicity, accompanied by an extension of the rapidity plateau while, on average, the particle transverse momentum shows little dependence upon the centre of mass (c.m.) energy [1]. These are the main features of soft hadronic interactions, where the vast majority of the particles are emitted with transverse momenta smaller than ≈ 1 GeV/c and the general characteristics of multiparticle production can be described by statistical models. With the high luminosities available in pp experiments it was however possible to observe phenomena with an underlying dynamics involving hadron constituents [2] as first seen in the study of deep inelastic lepton hadron collisions.

These observations have been confirmed a few years ago by the first results from the CERN proton-antiproton Collider experiments [3] at $\sqrt{s} = 0.546$ TeV. In this energy domain, even with low luminosities, it was possible to have new insights into the dynamics of multiparticle production. Recently, the successful operation of the SPS Collider in pulsed mode [4] has extended the study of hadron interactions over a wide c.m. energy range from 0.2 to 0.9 TeV.

In this paper we describe the general characteristics of proton-antiproton collisions up to $\sqrt{s} = 0.9$ TeV studied with the magnetic spectrometer and the calorimeter of UA1. In Sections 2 and 3 we report on the data taking with the SPS Collider operated in pulsed mode and in Section 4 we discuss the selection criteria used in the analysis. Results on charged particle multiplicities, transverse momenta, longitudinal momenta and on the total transverse energy are presented in Sections 5 to 8. In Section 9 we report a limit for the production of Centauro-type events [5] at 430 TeV/c equivalent laboratory momentum.

2. The Pulsed Collider.

In March 1985 the CERN SPS Collider attained its maximum c.m. energy of 0.9 TeV. The motivation for boosting the Collider operation up to the maximum SPS beam momentum was mainly the search for Centauro or other unusual events observed in cosmic ray experiments [5] in the region of around 10^3 TeV/c laboratory momentum.

The maximum energy of the SPS, operated with coasting beams, is limited by the average power dissipation in the main ring magnets, 47 MW at 315 GeV/c. To run at the maximum momentum of 450 GeV/c, it was proposed [6] to cycle the stored beam energy so that the larger power dissipation at 450 GeV/c was compensated by a lower dissipation at a lower beam momentum.

The SPS Collider was operated in pulsed mode between beam momenta of 100 and 450 GeV/c. The cycle was of 21.6 seconds with a flat top of 4.0 s, a flat bottom of 8.2 s and two energy ramps of 4.7 s each (see Fig.1). The SPS was operated in the normal beta scheme: $\beta_v = \beta_h = 50$ m and the beta values were measured to be independent of the beam momentum, ensuring that the luminosity was proportional to the beam energy to an accuracy of better than 1 % [4]. The choice of the beta values was dictated by the maximum current in the SPS quadrupoles. The beam intensity was kept low in order to minimize the beam losses at low momentum. With typically $6 \cdot 10^{10}$ protons and $6 \cdot 10^9$ antiprotons per bunch, in the mode of two proton bunches against one antiproton bunch, the average luminosity was about $10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ and the beam lifetime was of a few hours. The level of background in the UA1 detector was higher at low beam momentum due to the intrinsic dynamical properties of the machine [4] but, on the average, it was not worse than during the normal DC operation of the Collider.

The UA1 detector took data throughout the SPS cycle, the information of the beam momentum being recorded together with the data. It is worth noting that, when comparing data taken at different energies, many of the systematic effects due to the response of the detector and to the beam conditions cancel, since the data were recorded with the same circulating beams and in exactly the same experimental conditions.

3. The detector.

The UA1 detector provides magnetic and calorimetric analysis over a large solid angle. The main parts relevant for this analysis are the Central Detector, CD [7], which measures the momenta of charged particles in the pseudorapidity interval $|\eta| < 3.5$ and the calorimeter [8] which measures the energy deposited in $|\eta| < 6.0$ over the entire azimuthal angle. The field of the dipole magnet, usually set at 0.7 T, was lowered to 0.21 T in order to reduce the beam displacement in the centre of the detector. Small sets of data were taken without magnetic field and at 0.35 T to study systematic effects on the response of the detector with respect to normal runs at fixed energy.

The "minimum bias" trigger was a two-arm trigger that required at least two charged particles in opposite rapidity hemispheres in the range $1.5 < |\eta| < 5.5$. This trigger [9] accepts almost all of the inelastic non-diffractive cross section. The trigger cross section at $\sqrt{s} = 0.546$ TeV is derived from a comparison of the measurements of the total interaction rate made by UA1 [10] and UA4 [11] with a very similar hodoscope configuration. From the UA4 results, and from events recorded by triggering with the bunch crossing only, we derived a trigger cross section at $\sqrt{s} = 0.546$ TeV of 40 ± 4 mb, which corresponds to about 65 % of the total $\bar{p}p$ cross section. The effect of a different magnetic field on the trigger hodoscope rate is

negligible. From results of UA4 [12] and UA5 [13] we estimate the contribution from single diffractive events in our trigger to be less than 2 %. For the normalization at all other energies, only relative factors are needed since the SPS collider luminosity was proportional to the c.m. energy. Once the trigger cross section, σ_o^{tr} , at $E_o = 0.546$ TeV is known, we can derive the trigger cross section at any other energy:

$$\sigma^{\text{tr}} = (N/N_o) (E_o/E) (\Delta t_o / \Delta t) \rho \sigma_o^{\text{tr}}$$

where N is the number of events, E is the beam energy, Δt is the experiment live time and ρ is the ratio of the acceptances of the trigger and selection cuts (see Sec.4). The trigger cross section is plotted in Fig.2 as a function of the c.m. energy together with results on the total cross section and inelastic non single diffraction cross section from the Collider experiments [10-14] and from lower energy experiments. Both statistical and systematic errors on σ^{tr} are shown in the figure. The systematic uncertainty on the luminosity, due to the knowledge of the beam momentum, the measurement of the experiment live time and to the cuts applied to validate the trigger is on average ± 10 % [15]. The trigger rate was typically 1 Hz and 4 Hz at 0.2 and 0.9 TeV respectively. The data acquisition live time varied on average from 98 % at 0.2 TeV to 87 % at 0.9 TeV.

4. Data sample and selection criteria.

The present analysis is based on 188,000 events collected during the Pulsed Collider run in March 1985, 18 % at flat bottom, $\sqrt{s} = 0.2$ TeV, and 34 % at flat top, $\sqrt{s} = 0.9$ TeV, while 48 % of the events were taken in the energy ramps and have been subdivided for the analysis into five c.m. energy intervals centred at $\sqrt{s} = 0.26, 0.38, 0.50, 0.62$, and 0.79 TeV. The total integrated luminosity was $5.1 \mu\text{b}^{-1}$.

Events are retained for the analysis if they fulfil requirements on the timing of the trigger hodoscope, on the vertex reconstruction by the CD and on the total energy deposited in the calorimeter. These cuts reject background due to beam-gas interactions and halo particles that trigger the detector, and have been defined after a careful inspection of a number of events, taken in different beam conditions, with an interactive graphic display. The fraction of rejected triggers was 25 % at 0.2 TeV and 12 % at 0.9 TeV.

The main source of loss of $\bar{p}p$ inelastic interactions comes from demanding an interaction vertex reconstructed with at least two tracks in the region of good acceptance of the CD. This loss has been evaluated with the help of a Monte Carlo program [16] and amounts to 1.3 % at 0.2 TeV and 2.4 % at 0.9 TeV. Other losses due to the event selection criteria amount to less than 1% and show little dependence upon the c.m. energy. The residual background from beam gas interactions is 1.2 % at $\sqrt{s} = 0.2$ TeV and it is negligible at 0.9 TeV. As stressed in the previous section, only ratios between the efficiency and background corrections are relevant when comparing data at different c.m. energies.

Charged particle tracks reconstructed in the CD are accepted if they fulfil requirements on the track length, the fit χ^2 and association to the interaction vertex. Only those tracks with projected length, in the plane normal to the magnetic field, larger than 40 cm are considered for

the analysis. To reduce the contamination from photon conversions and secondary interactions in the beam pipe, only tracks with transverse momentum, p_T , larger than 0.15 GeV/c are retained. With these cuts, the average track finding efficiency is about 96 % almost independent of the event multiplicity [17].

The CD acceptance has been evaluated as a function of the charge, η , ϕ and p_T . Particles emitted in regions with acceptance lower than 20 % have not been considered and all tracks are weighted for the acceptance. Corrections due to strange particle decays, photon conversion and secondary interactions in the beam pipe contribute with a systematic error of ± 3 % to the quoted charged particle multiplicity, the uncertainty in the acceptance of the CD is on average ± 4 %.

Charged particle momenta are determined by their curvature in the magnetic field. Uncertainties due to systematic effects and to the track fitting result in an average measurement error $\delta p/p^2 = 0.005$ (GeV/c) $^{-1}$. For the longitudinal and transverse components, the measurement error is on average: $\delta p_L/p_L^2 = 0.01$ (GeV/c) $^{-1}$, $\delta p_T/p_T^2 = 0.03$ (GeV/c) $^{-1}$.

The event scalar transverse energy is obtained by summing the energies deposited in the calorimeter cells, $\Sigma E_T = \Sigma_i E_i \sin \theta_i$, where θ is the polar angle defined by the interaction vertex measured by the CD and the centre of gravity of the energy deposition in the calorimeter cells. The error on the measurement of the transverse energy, due to fluctuations of the energy deposition, is $\delta \Sigma E_T$ (GeV) $\approx 0.6 \sqrt{\Sigma E_T}$ /GeV. The systematic error due to the calibration of the calorimeter absolute energy scale is ± 8 %.

5. Charged particle multiplicity.

The topological cross section, $d\sigma/dn_{ch}$, for charged particles emitted in $|\eta| < 2.5$ is shown in Fig.3 and listed in Table 1 for different values of the c.m. energy. The overall systematic error due to uncertainties in the luminosity, in the selection criteria and acceptance corrections is ± 15 %.

The same multiplicity distributions are plotted in Fig.4 in terms of the KNO variables. The KNO hypothesis [18] implies that the normalized multiplicity distribution, $\langle n \rangle \sigma_n / \sigma$, behaves asymptotically as a universal function of the variable $z = n / \langle n \rangle$. Early results from the UA5 collaboration [19] have shown that KNO scaling is violated in non single diffractive collisions in the whole η range. For restricted pseudorapidity intervals, violations of KNO scaling have also been reported by UA5 [20], though the effect is less pronounced as the interval is reduced. The data plotted in Fig.4 are consistent with a unique distribution. The parameters extracted from the charged multiplicity distributions are plotted in Fig.5 as a function of the c.m. energy. In the same figure we also show results of non single diffractive collisions at $\sqrt{s} = 22$ GeV from NA22 in $|\eta| < 2.5$ [21] and at $\sqrt{s} = 0.546$ TeV from UA5 in $|\eta| < 3.0$ [22]. Scaling violations are signalled by changes in the C-moments of the distribution, $C_k = \langle n^k \rangle / \langle n \rangle^k$. The second moment C_2 shows a slight dependence upon $\sqrt{s}$ although this is less marked than for the UA5 data in a similar pseudorapidity interval. For a direct comparison with the UA5 results at $\sqrt{s} = 0.546$ TeV [19], the data at $\sqrt{s} = 0.5$ TeV are plotted in Fig.6 for

different pseudorapidity intervals. From these distributions it is evident that any departure from KNO scaling is mainly due to an excess of events with very large multiplicities ($z > 4$) in the UA5 data.

The charged particle density $dn_{ch}/d\eta$ measured at $\eta = 0$ is shown in Fig.7 as a function of the c.m. energy together with results from the UA5 collaboration [22,23] and data at lower energies. Our results are in good agreement with the non single diffractive data of UA5 and confirm the violation of Feynman scaling observed when increasing the c.m. energy from the ISR [24,25] to the SPS Collider. The data can be well fitted with a linear logarithmic law of the form: $dn_{ch}/d\eta = -0.32 + 0.55 \ln(\sqrt{s}/\text{GeV})$.

6. Transverse momentum distribution.

The invariant cross section for single charged particles, averaged over the interval $|\eta| < 2.5$, is plotted in Fig.8 as a function of the transverse momentum for $\sqrt{s} = 0.2$ and 0.9 TeV. The systematic error due to the luminosity and to the acceptance correction is $\pm 15\%$. Data from the ISR for charged and neutral pions are also shown in the figure. A clear increase of the high p_T tail is observed with increasing c.m. energy.

The data are well fitted with a power law of the form: $Ed^3\sigma/dp^3 = A (1 + p_T/p_{T0})^{-n}$ over the entire p_T range explored. At large transverse momenta a power law is suggested by the fragmentation of jets. Fig.9 shows the inclusive cross section at different c.m. energies with the fit superimposed. The same data are listed in Table 2 and the fit parameters are given in Table 3.

Even though the inclusive cross section is dominated by low p_T particles, the hardening of the p_T distribution with increasing c.m. energy implies an increase of the average transverse momentum. The average transverse momentum is computed by extrapolating the power law fit to $p_T = 0$. The values are shown in Fig.10 as a function of the c.m. energy and listed in Table 4. A remarkable increase of $\langle p_T \rangle$ with respect to measurements at the ISR [26] is observed. It has been suggested [27] that a better way to extrapolate the cross section to $p_T = 0$ would be by an exponential behaviour of the form $Ed^3\sigma/dp^3 = B \exp(-bm_T)$, where $m_T = (m_\pi^2 + p_T^2)^{1/2}$.

By fitting the data with an hybrid form of the type:

$$Ed^3\sigma/dp^3 = B \exp(-bm_T) \quad \text{for } p_T < p_T^*$$

$$Ed^3\sigma/dp^3 = A (1 + p_T/p_{T0})^{-n} \quad \text{for } p_T > p_T^*$$

with p_T^* as a free parameter, and constraining the function and its derivative at $p_T = p_T^*$, we obtain values of the average transverse momentum that are systematically higher by 6% though the χ^2 cannot discriminate between the two parametrizations. The two extrapolations to $p_T = 0$ imply different normalizations for the multiplicity cross sections reported in Section 5, though the difference is within the systematic errors. The data are well fitted with a quadratic logarithmic law of the form: $\langle p_T \rangle (\text{GeV}/c) = 0.40 - 0.030 \ln(\sqrt{s}/\text{GeV}) + 0.0053 (\ln(\sqrt{s}/\text{GeV}))^2$. To allow for different systematic errors, only the slope is fitted to the ISR data. The extrapolation to the Tevatron Collider energy is in fair agreement with the recent results of the E735 and CDF experiments [28].

From the analysis of minimum bias trigger data of the early 1981 run at $\sqrt{s} = 0.546$ TeV [29] we have reported a hardening of the p_T distribution with increasing charged multiplicity. The same effect is observed over the entire energy range explored here. Fig.11 shows the differential cross section for different intervals of charged multiplicity at $\sqrt{s} = 0.9$ TeV. The behaviour of the average transverse momentum as a function of the event charged multiplicity is shown in Fig.12 for $\sqrt{s} = 0.2$ and 0.9 TeV. Results from the Split Field Magnet at $\sqrt{s} = 63$ GeV [30] are also shown in the figure. Two points are of interest in the analysis of Fig.12: i) the average transverse momentum at low multiplicities is the same, within the systematic errors, over the large variation of c.m. energy and ii) at large multiplicities the average transverse momentum reaches a value that corresponds to the average p_T measured in events containing large E_T jets. This was observed by comparing minimum bias and jet trigger data at $\sqrt{s} = 0.63$ TeV [31]. The behaviour of the average transverse momentum with increasing multiplicity has been studied in terms of a phase transition [27,32] from a multiparticle state to a new state of quark-gluon plasma. A more conventional, though still debated, explanation is the correlation with the observed abundant production of low transverse energy clusters [33]. Large multiplicities and large transverse momenta can be interpreted as the result of gluon radiation from the interacting hadron constituents, or multiple low x parton-parton interactions.

7. Longitudinal momentum distributions.

The longitudinal momentum distribution of charged particles is studied in terms of the Feynman variable $x_F = 2p_L/\sqrt{s}$. Due to the limited acceptance of the detector in the forward region, the data do not explore the most interesting large x_F region, where the longitudinal momentum distribution of the emitted particles is expected to reflect that of the parent partons.

Fig. 13 shows the invariant cross section, $Ed^3\sigma/dp^3$, as a function of x_F for fixed values of the transverse momentum. Though the data are limited to low values of x_F , at these energies we expect the distribution to be insensitive to the particle masses and to depend mainly on the production mechanism. Data from proton-proton collisions showed scaling at medium values of x_F , $x_F = 0.1 - 0.3$, over the ISR energy range [34]. Results from those measurements and for comparable values of p_T are also shown in Fig.13. The ISR data overlap quite well with the data at $\sqrt{s} = 0.2$ TeV for $p_T = 0.4$ GeV/c, while for transverse momenta of 0.8 GeV/c or higher the Collider data have a larger cross section. Thus for transverse momenta close to $\langle p_T \rangle$, Feynman scaling appears to hold in a limited region, but there is a clear departure from scaling at small values of x_F . In fact, for any value of the transverse momentum, the invariant cross section at low values of x_F shows a continuous increase with the c.m. energy. Fig.14 shows this rise, including also data from the ISR [35]. The observed behaviour was predicted by non-scaling models in the form: $Ed^3\sigma/dp^3 \approx A s^\alpha$ [36]. From our data we obtain for the exponent a transverse momentum dependence of the form: $\alpha(p_T) = 0.14 + 0.13 (p_T/\text{GeV}/c)$

8. Transverse energy distribution.

The measurement of the total transverse energy deposited in the calorimeter, ΣE_T , provides global information about all neutral and charged particles. This information is complementary to the study of charged tracks and can be extended over a pseudorapidity interval larger than the acceptance of the CD.

Fig.15 shows the differential cross section, $d\sigma/d\Sigma E_T$, measured at different c.m. energies over the full acceptance of the calorimeter, $|\eta| < 6.0$. In order to compare this measurement with the charged multiplicity distributions, we introduce a continuous KNO-type variable [37] $z = \Sigma E_T / \langle \Sigma E_T \rangle$. Fig.16 shows the distribution $(1/\sigma) d\sigma/dz$ as a function of z for different c.m. energies. Over the entire pseudorapidity interval we observe a clear non scaling behaviour of the distribution. In the same figure we also show the fit to the charged multiplicity distribution measured by UA5 [23]. The two distributions should have the same behaviour in case of no correlation between multiplicity and transverse momenta. Since however, the calorimeter sums over all energies deposited by neutral and charged particles, a quantitative comparison needs a precise knowledge of the difference in the calorimeter response to neutral and charged particles at low energy. Indeed a correlation exists between transverse energy and charged multiplicity as shown in Fig.17 where both ΣE_T and n_{ch} are measured over the same interval $|\eta| < 2.5$. The behaviour of $\Sigma E_T / n_{ch}$ is rapidly changing over the explored energy range. At $\sqrt{s} = 0.2$ TeV, where $\Sigma E_T / n_{ch} \approx \text{constant}$, the UA1 and UA5 distributions are in reasonable agreement while the difference is more marked at higher energy.

The dependence of the transverse energy density, $d\Sigma E_T/d\eta$, measured at $\eta = 0$ as a function of the c.m. energy is shown in Fig.18 together with results from the ISR [38]. This measurement complements those shown in figs. 7 and 10 on the multiplicities and transverse momenta of charged particles. The data show an increase with the c.m. energy faster than $\ln s$, the line in Fig.18 is a quadratic logarithmic fit: $d\Sigma E_T/d\eta \text{ (GeV)} = 0.80 - 0.075 \ln(\sqrt{s}/\text{GeV}) + 0.051(\ln(\sqrt{s}/\text{GeV}))^2$.

In Table 4 we summarize the results on $\langle dn_{ch}/d\eta \rangle$, $\langle p_T \rangle$ and $\langle d\Sigma E_T/d\eta \rangle$ measured in the central region. For comparison with other measurements one should recall that the present results refer mainly to non diffractive events, as discussed in Section 3.

9. Search for Centauro-like events.

The Centauro events observed in emulsion chambers exposed to cosmic rays are very high energy events characterized by a very large multiplicity of hadrons and a multiplicity of electromagnetic showers that is consistent with zero. Limits on the production cross section for such events at $\sqrt{s} = 0.546$ TeV have been published [39,40]. An analysis similar to that described in ref. [40] has been done on 67,000 events at $\sqrt{s} = 0.9$ TeV.

A statistical separation between the electromagnetic and the hadronic visible energy is done exploiting the longitudinal segmentation of the calorimeter. The best sensitivity is obtained by comparing the energy deposited in the first 4 radiation lengths with that deposited after 12 radiation lengths. In Fig.19 we show the correlation of the two energy depositions for events

with charged multiplicity $n_{ch} > 10$ and transverse momentum, averaged over all charged particles, $\langle p_T \rangle > 1$ GeV/c, for the barrel ($30^\circ < \theta < 150^\circ$) and end-cap ($5^\circ < \theta < 30^\circ$, $150^\circ < \theta < 175^\circ$) calorimeters separately. Following the analysis of ref. [40], the Centauro events for which there is enough information to make a Lorentz transformation to the c.m. system will be located in the position indicated in Fig.19 for a decay or a collision hypothesis. The two locations correspond to two extreme assumptions for the fraction K_γ of the total hadronic energy that is converted into electromagnetic showers: $K_\gamma = 0.33$ (A) for production of mesons, $K_\gamma = 0.2$ (B) for production of nucleon-antinucleon pairs. No event is compatible with the decay hypothesis. A search for high multiplicity secondary vertices has shown that these occur on the vacuum pipe or on the CD walls. All events shown in Fig.19b have been scanned with a high resolution interactive display and they are compatible with Monte Carlo [16] predictions with no Centauro event simulation. In general these events show a cluster structure both in the CD and in the calorimeter. On the basis of this result we can place a limit of around one microbarn for the production of event configurations similar to the Centauro events. This limit is more stringent than the limit reported by the UA5 Collaboration at $\sqrt{s} = 0.9$ TeV [41].

10. Conclusions.

We have exploited the unique opportunity provided by the SPS Pulsed Collider to study with the same detector, the same beams and within the cycle time of a few seconds, the general characteristics of minimum bias proton-antiproton collisions in a wide range of centre of mass energy. This range extends from $\sqrt{s} = 0.2$ TeV, three times the maximum ISR energy, to $\sqrt{s} = 0.9$ TeV, one half of the Tevatron Collider energy.

Results have been presented on the multiplicity, transverse and longitudinal momentum distributions of charged particles, measured with the magnetic spectrometer, and on the transverse energy distribution, measured with the calorimeter. Most of the systematic errors, discussed in the text, have no influence on the results when studying the energy dependence of the measured quantities.

Over the explored energy interval we observe a logarithmic increase of the charged multiplicity density in the central region. The shape of the charged multiplicity distribution, in terms of the KNO variables, is consistent with KNO scaling in the restricted pseudorapidity interval $|\eta| < 2.5$. We observe for charged particles a strong energy dependent correlation between transverse momentum and multiplicity. As a result of this correlation, the transverse energy increases with c.m. energy faster than $\ln s$. The study of the longitudinal momentum distributions shows a marked departure from Feynman scaling in the very low x_F region.

No unusual phenomenon has been observed at $\sqrt{s} = 0.9$ TeV with a sensitivity of 1.3 events/ μb . We can place a limit of around one microbarn, at 430 TeV/c equivalent laboratory momentum, for the production of event configurations with characteristics similar to the Centauro events observed in cosmic ray experiments.

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Table 1
Topological cross section $d\sigma/dn_{ch}$ (mb)

n_{ch}	$\sqrt{s} = 0.2 \text{ TeV}$	$\sqrt{s} = 0.5 \text{ TeV}$	$\sqrt{s} = 0.9 \text{ TeV}$
2	1.654 $\pm$ 0.042	1.509 $\pm$ 0.066	1.475 $\pm$ 0.030
4	2.080 $\pm$ 0.047	2.110 $\pm$ 0.078	2.166 $\pm$ 0.036
6	3.532 $\pm$ 0.062	3.166 $\pm$ 0.095	2.978 $\pm$ 0.043
8	3.488 $\pm$ 0.062	3.524 $\pm$ 0.100	3.614 $\pm$ 0.047
10	3.692 $\pm$ 0.063	3.552 $\pm$ 0.101	3.608 $\pm$ 0.047
12	3.426 $\pm$ 0.061	3.672 $\pm$ 0.102	3.680 $\pm$ 0.047
14	3.016 $\pm$ 0.057	3.434 $\pm$ 0.099	3.334 $\pm$ 0.045
16	2.690 $\pm$ 0.054	2.966 $\pm$ 0.092	3.018 $\pm$ 0.043
18	2.252 $\pm$ 0.049	2.502 $\pm$ 0.084	2.652 $\pm$ 0.040
20	1.840 $\pm$ 0.045	2.264 $\pm$ 0.080	2.414 $\pm$ 0.038
22	1.474 $\pm$ 0.040	1.887 $\pm$ 0.073	2.124 $\pm$ 0.036
24	1.200 $\pm$ 0.036	1.634 $\pm$ 0.068	1.881 $\pm$ 0.034
26	1.012 $\pm$ 0.033	1.361 $\pm$ 0.062	1.655 $\pm$ 0.032
28	0.782 $\pm$ 0.029	1.230 $\pm$ 0.059	1.486 $\pm$ 0.030
30	0.617 $\pm$ 0.026	1.019 $\pm$ 0.054	1.313 $\pm$ 0.028
32	0.510 $\pm$ 0.024	0.846 $\pm$ 0.049	1.201 $\pm$ 0.027
34	0.324 $\pm$ 0.019	0.789 $\pm$ 0.047	1.027 $\pm$ 0.025
36	0.268 $\pm$ 0.017	0.643 $\pm$ 0.043	0.910 $\pm$ 0.024
38	0.228 $\pm$ 0.016	0.493 $\pm$ 0.037	0.744 $\pm$ 0.021
40	0.156 $\pm$ 0.013	0.370 $\pm$ 0.032	0.620 $\pm$ 0.019
42	0.104 $\pm$ 0.011	0.293 $\pm$ 0.029	0.559 $\pm$ 0.018
44	0.0802 $\pm$ 0.0093	0.262 $\pm$ 0.027	0.421 $\pm$ 0.016
46	0.0586 $\pm$ 0.0080	0.256 $\pm$ 0.027	0.385 $\pm$ 0.015
48	0.0369 $\pm$ 0.0063	0.157 $\pm$ 0.021	0.278 $\pm$ 0.013
50	0.0217 $\pm$ 0.0049	0.140 $\pm$ 0.020	0.234 $\pm$ 0.012
52	0.0174 $\pm$ 0.0043	0.105 $\pm$ 0.017	0.181 $\pm$ 0.010
54	0.0119 $\pm$ 0.0036	0.057 $\pm$ 0.013	0.153 $\pm$ 0.010
56		0.0342 $\pm$ 0.0099	0.1141 $\pm$ 0.0083
58	0.0060 $\pm$ 0.0018		0.0941 $\pm$ 0.0076
60		0.0228 $\pm$ 0.0057	0.0607 $\pm$ 0.0061
62	0.0021 $\pm$ 0.0012		0.0561 $\pm$ 0.0060
64		0.0115 $\pm$ 0.0035	0.0474 $\pm$ 0.0056
66			0.0279 $\pm$ 0.0044
68			0.0175 $\pm$ 0.0036
70			0.0091 $\pm$ 0.0026
74		0.0019 $\pm$ 0.0011	0.0078 $\pm$ 0.0018
78			0.0033 $\pm$ 0.0010
84			0.0011 $\pm$ 0.0008

Table 2
Invariant cross section of charged hadrons at $\eta = 0$ (mb/GeV²).

p_T (GeV/c)	$\sqrt{s} = 0.2$ TeV	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 0.9$ TeV
0.25	62.0 $\pm$ 3.1	88.3 $\pm$ 4.4	115.6 $\pm$ 5.8
0.35	36.2 $\pm$ 1.8	50.9 $\pm$ 2.6	66.9 $\pm$ 3.3
0.45	20.8 $\pm$ 1.0	29.2 $\pm$ 1.5	39.5 $\pm$ 2.0
0.55	12.32 $\pm$ 0.62	17.86 $\pm$ 0.90	24.2 $\pm$ 1.2
0.65	7.33 $\pm$ 0.37	10.77 $\pm$ 0.55	15.0 $\pm$ 0.75
0.75	4.54 $\pm$ 0.23	6.81 $\pm$ 0.35	9.54 $\pm$ 0.48
0.85	2.77 $\pm$ 0.14	4.34 $\pm$ 0.22	6.17 $\pm$ 0.31
0.95	1.724 $\pm$ 0.088	2.68 $\pm$ 0.14	4.05 $\pm$ 0.20
1.05	1.162 $\pm$ 0.060	1.93 $\pm$ 0.10	2.85 $\pm$ 0.14
1.15	0.769 $\pm$ 0.040	1.190 $\pm$ 0.064	1.98 $\pm$ 0.10
1.25	0.521 $\pm$ 0.028	0.888 $\pm$ 0.048	1.372 $\pm$ 0.070
1.35	0.344 $\pm$ 0.019	0.599 $\pm$ 0.033	0.948 $\pm$ 0.048
1.45	0.240 $\pm$ 0.013	0.445 $\pm$ 0.026	0.691 $\pm$ 0.035
1.55	0.1680 $\pm$ 0.0095	0.302 $\pm$ 0.018	0.501 $\pm$ 0.029
1.65	0.1180 $\pm$ 0.0069	0.232 $\pm$ 0.014	0.375 $\pm$ 0.019
1.75	0.0861 $\pm$ 0.0053	0.173 $\pm$ 0.011	0.266 $\pm$ 0.014
1.85	0.0579 $\pm$ 0.0038	0.1206 $\pm$ 0.0083	0.201 $\pm$ 0.011
1.95	0.0440 $\pm$ 0.0030	0.0854 $\pm$ 0.0064	0.1585 $\pm$ 0.0085
2.05	0.0308 $\pm$ 0.0023	0.0725 $\pm$ 0.0056	0.1114 $\pm$ 0.0061
2.15	0.0223 $\pm$ 0.0018	0.0551 $\pm$ 0.0045	0.0903 $\pm$ 0.0050
2.25	0.0167 $\pm$ 0.0014	0.0385 $\pm$ 0.0035	0.0681 $\pm$ 0.0039
2.35	0.0143 $\pm$ 0.0013	0.0293 $\pm$ 0.0029	0.0555 $\pm$ 0.0032
2.45	0.0092 $\pm$ 0.0010	0.0235 $\pm$ 0.0025	0.0404 $\pm$ 0.0025
2.55	0.00575 $\pm$ 0.00071	0.0171 $\pm$ 0.0020	0.0326 $\pm$ 0.0020
2.65	0.00558 $\pm$ 0.00069	0.0122 $\pm$ 0.0016	0.0235 $\pm$ 0.0016
2.75	0.00376 $\pm$ 0.00054	0.0107 $\pm$ 0.0015	0.0209 $\pm$ 0.0014
2.85	0.00362 $\pm$ 0.00052	0.0080 $\pm$ 0.0013	0.0163 $\pm$ 0.0012
2.95	0.00322 $\pm$ 0.00048	0.0073 $\pm$ 0.0012	0.0126 $\pm$ 0.0010
3.05	0.00191 $\pm$ 0.00035	0.0059 $\pm$ 0.0010	0.00997 $\pm$ 0.00080
3.15	0.00179 $\pm$ 0.00034	0.00293 $\pm$ 0.00070	0.00869 $\pm$ 0.00072
3.25	0.00126 $\pm$ 0.00028	0.00467 $\pm$ 0.00089	0.00586 $\pm$ 0.00055
3.35	0.00155 $\pm$ 0.00030	0.00282 $\pm$ 0.00067	0.00492 $\pm$ 0.00049
3.45	0.00072 $\pm$ 0.00020	0.00216 $\pm$ 0.00057	0.00359 $\pm$ 0.00040
3.55	0.00060 $\pm$ 0.00018	0.00100 $\pm$ 0.00027	0.00397 $\pm$ 0.00042
3.65	0.000286 $\pm$ 0.000086		0.00355 $\pm$ 0.00039
3.75			0.00240 $\pm$ 0.00030
3.85	0.000389 $\pm$ 0.000098	0.00130 $\pm$ 0.00030	0.00204 $\pm$ 0.00027
3.95			0.00191 $\pm$ 0.00026
4.10	0.000172 $\pm$ 0.000051	0.00058 $\pm$ 0.00016	0.00135 $\pm$ 0.00015
4.30			0.00085 $\pm$ 0.00011
4.50	0.000114 $\pm$ 0.000035	0.000301 $\pm$ 0.000094	0.00061 $\pm$ 0.00010
4.70			0.000495 $\pm$ 0.000082
4.90		0.000161 $\pm$ 0.000049	0.000343 $\pm$ 0.000068
5.10			0.000223 $\pm$ 0.000053
5.30			0.000141 $\pm$ 0.000041
5.50			0.000155 $\pm$ 0.000042
5.70	0.0000135 $\pm$ 0.0000067		0.000110 $\pm$ 0.000035
5.90		0.000045 $\pm$ 0.000020	0.000078 $\pm$ 0.000023
6.50			0.0000245 $\pm$ 0.0000076
6.70	0.0000066 $\pm$ 0.0000043		
7.30		0.000008 $\pm$ 0.000006	0.0000210 $\pm$ 0.0000067
8.20			0.0000064 $\pm$ 0.0000031
9.20			0.0000066 $\pm$ 0.0000030

T a b l e 3

Parameters of the fit to the inclusive p_T distribution $Ed^3\sigma/dp^3 = A(1 + p_T/p_{T0})^{-n}$

$\sqrt{s}$ (GeV)	A (mb/GeV ²)	p_{T0} (GeV/c)	n
0.20	286 ± 17	1.80 ± 0.10	12.14 ± 0.39
0.26	230 ± 19	1.85 ± 0.12	12.15 ± 0.50
0.38	362 ± 23	1.53 ± 0.09	10.51 ± 0.35
0.50	408 ± 24	1.61 ± 0.08	10.64 ± 0.31
0.62	382 ± 22	1.54 ± 0.08	10.24 ± 0.28
0.79	390 ± 20	1.53 ± 0.06	10.16 ± 0.23
0.90	382 ± 20	1.56 ± 0.05	9.96 ± 0.17

T a b l e 4

Average charged multiplicity density, transverse momentum and transverse energy density measured at $\eta = 0$. (The systematic errors are discussed in the text).

$\sqrt{s}$ (TeV)	$\langle dn_{ch}/d\eta \rangle$	$\langle p_T \rangle$ (GeV/c)	$\langle d\Sigma E_T/d\eta \rangle$ (GeV)
0.20	2.65 ± 0.08	0.392 ± 0.003	1.85 ± 0.01
0.26	2.71 ± 0.08	0.404 ± 0.004	1.94 ± 0.02
0.38	2.94 ± 0.09	0.408 ± 0.004	2.12 ± 0.02
0.50	3.05 ± 0.09	0.419 ± 0.004	2.29 ± 0.02
0.62	3.15 ± 0.09	0.426 ± 0.004	2.39 ± 0.02
0.79	3.41 ± 0.10	0.435 ± 0.004	2.59 ± 0.02
0.90	3.48 ± 0.10	0.447 ± 0.003	2.66 ± 0.02

Figure captions

- Fig.1** The cycle of the SPS Collider operated in pulsed mode.
- Fig.2** The trigger cross section as a function of the c.m. energy compared with results of the non single diffractive and total cross section measured at the Collider and at lower energies. The full line is the σ_{tot} fit of ref. [42], the dashed line is $2/3 \sigma_{\text{tot}}$.
- Fig.3** Topological cross sections for $|\eta| < 2.5$ as a function of the charged particle multiplicity.
- Fig.4** KNO multiplicity distributions for $|\eta| < 2.5$.
- Fig.5** a) Average charged multiplicity and b) second moment of the multiplicity distribution as a function of the c.m. energy.
- Fig.6** KNO multiplicity distributions in different intervals of pseudorapidity: a) $|\eta| < 0.5$, b) $|\eta| < 1.5$.
- Fig.7** Average charged particle multiplicity measured at $\eta = 0$ as a function of the c.m. energy.
- Fig.8** Inclusive cross section for single charged hadrons as a function of the transverse momentum.
- Fig.9** Inclusive cross section for single hadrons as a function of the transverse momentum. The fit is of the form: $A(1 + p_T/p_{T0})^{-n}$.
- Fig.10** Average transverse momentum of charged particles as a function of the c.m. energy.
- Fig.11** Inclusive cross section for single charged hadrons as a function of the transverse momentum for different multiplicities. The curves are normalized to the same value at $p_T = 0.2 \text{ GeV}/c$.
- Fig.12** Average transverse momentum as a function of the charged particle multiplicity.
- Fig.13** Inclusive cross section for single charged hadrons as a function of x_F for different values of the c.m. energy. The ISR data are from ref. [34].
- Fig.14** Inclusive cross section for single charged hadrons as a function of $\sqrt{s}$ for $x_F = 0$. The ISR data are from ref. [35].
- Fig.15** Transverse energy differential cross section for different values of the c.m. energy.
- Fig.16** Transverse energy distribution in terms of the scaling variable $z = \Sigma E_T / \langle \Sigma E_T \rangle$.
- Fig.17** Transverse energy (a) and transverse energy per charged particle (b) measured in $|\eta| < 2.5$ as a function of the charged particle multiplicity.
- Fig.18** Transverse energy density, $d\Sigma E_T/d\eta$, measured at $\eta = 0$ as a function of the c.m. energy.
- Fig.19** Correlation of the energies deposited in the first 4 radiation lengths and beyond 12 radiation lengths in the barrel (a) and in the end-cap (b) calorimeter for all events with $n_{\text{ch}} > 10$ and $\langle p_T \rangle > 1 \text{ GeV}/c$.

FIG. 1

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