CERN/EP 85-31
7 March 1985

ELASTIC SCATTERING AT THE CERN SPS COLLIDER

UP TO A FOUR-MOMENTUM TRANSFER OF 1.55 GeV^2

UA4 Collaboration

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ABSTRACT

Proton-antiproton elastic scattering was measured at the centre-of-mass energy $\sqrt{s} = 546 \text{ GeV}$ in the four-momentum transfer range $0.45 \leq -t \leq 1.55 \text{ GeV}^2$. The shape of the t -distribution is quite different from that observed in proton-proton scattering at the ISR. Rather than a dip-bump structure, a kink is present at $-t \approx 0.9 \text{ GeV}^2$ followed by a shoulder. The cross section at the second maximum is more than one order of magnitude higher than at the ISR.

Submitted to Physics Letters B

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Results are presented on proton-antiproton elastic scattering at $\sqrt{s} = 546$ GeV in the momentum transfer range $0.45 \leq -t \leq 1.55$ GeV². These data extend to higher momentum transfer our earlier measurements [1] which covered the range $0.03 \leq -t \leq 0.5$ GeV². A schematic view of the experimental apparatus at the CERN SPS Collider is shown in fig. 1. The experimental technique is the same as was used previously [1]. Elastic scattering events are observed by a system of sixteen detectors placed inside movable sections ("roman pots") of the SPS vacuum chamber. Each detector consists of a scintillation counter hodoscope and a wire chamber. The wire chamber provides a point measurement with resolutions of 0.07 mm and 0.4 mm in the vertical and horizontal coordinates, respectively. The "pots" are arranged in two groups of four telescopes placed symmetrically with respect to the crossing point, above and below the machine plane. The "outer" telescopes are at a distance of about 40 m from the crossing point while the "inner" telescopes are at about 25 m. Each telescope is composed of two detectors that are 6 m and 3 m apart for the "outer" and "inner" telescopes, respectively.

The present data were collected during the 1982 and 1983 Collider runs with two different machine optics, the low- β and the squeezed- β mode. The average luminosity was about 5×10^{28} cm⁻²s⁻¹. The integrated luminosity in the squeezed- β runs was twice as large as for the low- β runs. At the crossing point the betatron functions in the horizontal and vertical plane were $\beta_h = 2$ m, $\beta_v = 1$ m for the low- β mode and $\beta_h = 1.3$ m, $\beta_v = 0.65$ m for the squeezed- β mode. In the vertical plane the r.m.s. values of the size and angular spread of the beam at the crossing were typically about 0.14 mm and 0.14 mrad for the low- β mode. For the squeezed- β mode the corresponding figures were 0.11 mm and 0.16 mrad.

Particles scattered in the crossing region traverse the quadrupoles Q_F and Q_D of the machine lattice before reaching the detectors. In the vertical plane Q_F and Q_D act as focussing and defocussing lenses, respectively. The quadrupole Q_F produces a deflection by an angle of about $2\theta_v$, where θ_v is the vertical component of the scattering angle. The deflection by the quadrupole Q_D is approximately equal to θ_v . The low- β optics is not fully left-right symmetric with respect to the crossing point. As a consequence the "outer" detectors on the right side (outgoing proton side) could not be used when running with this optics. In the

squeezed- β mode, on the other hand, all detectors were used. The deflection through the quadrupoles was calculated with the standard formalism of transfer matrices using the accurately known strength and effective length of the quadrupoles. The integrated gradient varies by less than 3×10^{-3} over the useful aperture of the quadrupoles. Each track observed in a telescope was reconstructed back to the crossing region with errors depending only on the detector resolution and on multiple scattering in the pot windows and counters. The aperture of the vacuum chamber inside the quadrupole Q_F limits the maximum scattering angle which can be detected to about 4.5 mrad. The trajectory in the vertical plane for a scattering angle of 2.5 mrad with low- β optics is also shown in fig. 1. More details on the detectors and the operation of the system are given in ref. [2].

The trigger was provided by the left-right coincidence of the trigger counters of two opposite arms. It was a 6-fold coincidence for the low- β and a 8-fold coincidence for the squeezed- β mode. The deflection through the machine quadrupoles allowed a powerful momentum selection. Particles coming from the crossing region with a momentum less than about 13% of the beam momentum were not even accepted by the trigger [3]. About 6×10^5 triggers were collected. Calibration and detection efficiency of the wire chambers were studied using the data collected with the elastic trigger itself. In the track reconstruction procedure a hit was required in at least five of the eight drift planes and in at least one of the two proportional planes in a telescope. Due to the redundancy in the number of planes a fully efficient detection could be ensured over the telescope acceptance.

The analysis was carried out according to the following steps:

- (a) A single track was demanded in each telescope of two opposite arms without tracks in the other telescopes.
- (b) Events were rejected if a hit was present in a system [2] of scintillation counter hodoscopes covering the pseudorapidity range $2.5 \leq |\eta| \leq 5.6$ on both sides of the crossing region.
- (c) A three-standard-deviation cut was applied to the distributions of the vertical coordinate y_0 of the proton and antiproton trajectories at the centre of the crossing region.

Examples of these distributions for different intervals of momentum transfer are shown in fig. 2. A cut on the quantity y_0 is equivalent to a momentum analysis on both scattered particles. A three-standard-deviation cut corresponds to a selection of events where the momentum of both p and $\bar{p}$ is within 2% of the beam momentum. The natural momentum spread of the circulating beam is only a few times 10^{-4} .

A sample of about 2×10^5 elastic events was left after applying a three-standard-deviation cut to the collinearity distributions of the proton and antiproton trajectories in the vertical plane. Examples of the collinearity distributions as obtained after selections (a), (b) and (c) are also shown in fig. 2 for different intervals of t . A clear signal of elastic scattering events with negligible background is seen also at the large values of momentum transfer. The width of the collinearity distributions is determined by the intrinsic angular spread of the beam while the width of the y_0 distributions results from measurement errors and is much wider than the actual beam size.

The uncertainty on the scattering angle is determined by the intrinsic angular spread of the beam. The observed width of the collinearity distributions provides a direct measurement of this quantity which agrees well with the value calculated from the known machine parameters. Its r.m.s. value is about 0.1 mrad, the same for both optics within 20%. This implies a r.m.s. t -resolution $\Delta t = 0.06\sqrt{|t|}$.

The strong variation with t of the differential cross section allowed an accurate determination of the actual angle of the beam with respect to the nominal machine axis. By comparing the trend of the observed angular distributions for the two arms (up-left $\times$ down-right) and (down-left $\times$ up-right) it was found that the vertical component of the beam angle was 0.05 mrad and 0.03 mrad for the low- β and squeezed- β optics, respectively. These results were confirmed by the measurements provided by the beam position monitors. The true scattering angle was then calculated by taking the average of the observed production angles of the proton and antiproton, corrected for the beam angle.

The geometrical acceptance of the detectors as a function of t was carefully studied by varying the accepted interval of θ_h (the horizontal component of the scattering angle) in order to ensure clearance inside the quadrupole vacuum chamber. The acceptance was calculated with a Monte-Carlo that takes into account the size, angular spread and the angle of the incoming beams. About 4.5×10^4 events were retained within the interval $|\theta_h| \leq 0.15$ mrad. It was checked that the t -dependence of the data remained the same when further reducing the accepted interval of $|\theta_h|$.

The absolute normalization of the t -distribution was obtained by smoothly joining the present data to our earlier measurements [1] which extend up to 0.5 GeV^2 . The results are shown in fig. 3 and listed in table 1, where the quoted errors are only statistical. An additional scale error of 10% is present due to the joining of the two sets of data and to the normalization error of the data of ref. [1]. No dip is observed in the data which show an exponential decrease with momentum transfer and a break at $-t \approx 0.9 \text{ GeV}^2$ followed by a shoulder. Above 0.9 GeV^2 the differential cross section is of the order of $1 \text{ } \mu\text{b/GeV}^2$ and decreases slowly with t . In the region of the exponential decrease the data points were corrected for the smearing due to the finite t -resolution by an amount varying up to 12%. Our preliminary, low-statistics, data collected in the 1982 Collider run, which were reported previously [4], agree well with the final data presented in this letter.

The proton-proton elastic scattering data at ISR energies [5] were fitted using a sum of two interfering amplitudes with exponential t -dependence,

$$d\sigma/dt \sim |e^{b(t-t_0)/2} + e^{d(t-t_0)/2+i\phi}|^2$$

Complete destructive interference would occur at $t = t_0$ if the relative phase ϕ is equal to π . Also the present data are well represented by the previous expression. A fit in the range $0.21 \leq -t \leq 1.55 \text{ GeV}^2$ gave the following results:

$$b = 12.9 \pm 0.1 \text{ GeV}^{-2}$$

$$d = 2.4 \pm 0.2 \text{ GeV}^{-2}$$

$$-t_0 = 0.83 \pm 0.01 \text{ GeV}^2$$

$$\phi = \pi - (0.82 \pm 0.04)$$

with $\chi^2 = 51$ for 56 degrees of freedom. The relatively large value of the phase difference $\phi - \pi$ reflects the absence of a dip in the data.

The Collider results on $\bar{p}p$ elastic scattering at $\sqrt{s} = 546$ GeV are plotted in fig. 4 together with pp data measured at the ISR at $\sqrt{s} = 53$ GeV [5-7]. The value of the differential cross section on the second maximum is more than one order of magnitude higher at the Collider than at ISR energies. In contrast to the ISR data, only a shoulder is present above $-t \approx 0.9$ GeV². It is clear that the t -resolution of this experiment would be sufficient to observe such a prominent dip-bump structure as is seen at the ISR.

Recent $\bar{p}p$ results at $\sqrt{s} = 53$ GeV [7,8] in the range $0.1 \leq -t \leq 3.5$ GeV² have shown that at this energy $\bar{p}p$ elastic scattering is essentially undistinguishable from pp scattering, except in the region of the dip which appears to be significantly less pronounced in $\bar{p}p$ scattering.

The dramatic increase with energy of the differential cross section at the second maximum which is observed in this experiment confirms, at least qualitatively, the prediction of the eikonal type models [9]. These models also predicted that, as the total cross section rises with energy, also the ratio of the elastic to the total cross section would increase. A rise of this cross section ratio has been in fact experimentally observed at the Collider [10].

Our earlier preliminary data [4] have been discussed in several theoretical papers [11]. A model independent analysis [12] of the elastic scattering data at the Collider, performed in terms of the impact parameter representation of the scattering amplitude strongly suggests the following interpretation, in agreement with the predictions of ref. [9]. As the energy goes up from the ISR to the Collider, the effective interaction radius of the proton increases. In addition the proton itself becomes more absorbing in the central region at small values of the impact parameter.

We wish to express our gratitude to the staff of the CERN Accelerator Divisions for the help in the installation and survey of this experiment and for the successful operation of the SPS Collider. The continued effort of the technicians at CERN, INFN and NIKHEF who contributed to this experiment is warmly acknowledged.

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TABLE 1

Differential cross section at $\sqrt{s} = 546$ GeV

$-t$ GeV ²	$d\sigma/dt$ mb/GeV ²	Error mb/GeV ²
.46	2.932 E-01	5.7 E-03
.48	2.241 E-01	3.8 E-03
.50	1.786 E-01	2.8 E-03
.52	1.308 E-01	2.4 E-03
.54	1.003 E-01	2.1 E-03
.56	7.440 E-02	1.0 E-03
.58	5.641 E-02	8.8 E-04
.60	4.170 E-02	7.6 E-04
.62	3.194 E-02	6.6 E-04
.64	2.211 E-02	5.5 E-04
.66	1.792 E-02	5.0 E-04
.68	1.267 E-02	4.2 E-04
.70	9.55 E-03	3.7 E-04
.73	6.26 E-03	2.1 E-04
.77	3.71 E-03	1.6 E-04
.81	2.47 E-03	1.4 E-04
.85	1.76 E-03	1.2 E-04
.89	1.39 E-03	1.1 E-04
.93	1.50 E-03	1.2 E-04
.97	1.44 E-03	1.2 E-04
1.01	1.26 E-03	1.2 E-04
1.05	1.17 E-03	1.1 E-04
1.09	1.35 E-03	1.2 E-04
1.13	1.19 E-03	1.2 E-04
1.17	1.27 E-03	1.2 E-04
1.21	0.87 E-03	1.0 E-04
1.25	1.17 E-03	1.2 E-04
1.29	1.04 E-03	1.1 E-04
1.33	8.40 E-04	1.0 E-04
1.37	9.39 E-04	1.1 E-04
1.41	9.51 E-04	1.1 E-04
1.45	6.90 E-04	9.5 E-05
1.49	5.40 E-04	8.4 E-05
1.53	5.06 E-04	8.2 E-05

FIGURE CAPTIONS

- Fig. 1 Schematic view of one side of the experimental layout. The apparatus is symmetric with respect to the crossing point. The position of the detectors and of the machine quadrupoles is indicated. The trajectory in the vertical plane for the low- β optics corresponding to a scattering angle of 2.5 mrad is also shown.
- Fig. 2 The vertical displacement of the antiproton and proton trajectories at the centre of the crossing region, $y_0(\bar{p})$ and $y_0(p)$ respectively, are shown together with collinearity plots in the vertical plane. The upper, middle and lower section refer to the following three intervals of momentum transfer, $0.55 \leq -t \leq 0.8 \text{ GeV}^2$, $0.8 \leq -t \leq 1.2 \text{ GeV}^2$ and $1.2 \leq -t \leq 1.5 \text{ GeV}^2$, respectively.
- Fig. 3 The proton-antiproton differential cross section of elastic scattering at c.m.s. energy 546 GeV. Our earlier measurements [1] for $-t \leq 0.5 \text{ GeV}^2$ are plotted together with the results of the present experiment. The r.m.s. t -resolution at $-t = 1 \text{ GeV}^2$ is 0.06 GeV^2 .
- Fig. 4 The $\bar{p}p$ elastic scattering data at the SPS Collider ($\sqrt{s} = 546 \text{ GeV}$) are compared to pp data at the ISR ($\sqrt{s} = 53 \text{ GeV}$) from refs. [5-7].

ELASTIC SCATTERING LAYOUT

Fig. 1

Fig. 2

Fig. 3

Fig. 4