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Elastic Scattering of Charged Mesons, Antiprotons and Protons
on Protons at Incident Momenta of 20, 30 and 50 GeV/c
in the Momentum Transfer Range $0.5 < -t < 8 \text{ (GeV/c)}^2$.

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Abstract

Results are presented from experiment WA7 at the CERN SPS, which has measured the elastic differential cross sections of $\pi^{\pm}p$, $K^{\pm}p$, $\bar{p}p$ and pp at incident momenta of 20, 30 and 50 GeV/c. The measurements cover the momentum transfer range $0.5 < |t| < 8 \text{ (GeV/c)}^2$, corresponding to c.m. scattering angles between 10 and 50°. The experimental set-up, trigger logic and data analysis are described. The experimental results are compared with existing meson-proton and nucleon-proton data at lower and higher energies covering the medium- and large- $|t|$ region. Some prominent models and their predictions for elastic scattering at WA7 energies and beyond are reviewed, with emphasis on geometrical scaling, factorizing eikonal models, lowest order QCD and other dynamical exchange-type models. Results for $\bar{p}p$ two-body annihilation into $\pi^-\pi^+$ and K^-K^+ at 30 and 50 GeV/c, obtained in parallel with the elastic $\bar{p}p$ data, are also presented.

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1. INTRODUCTION

The CERN SPS experiment WA7 has measured the elastic differential cross sections of $\pi^{\pm}p$, $K^{\pm}p$, $\bar{p}p$ and pp scattering at incident momenta of 20, 30 and 50 GeV/c in the momentum transfer range $0.5 < |t| < 8$ (GeV/c)². This paper describes the experiment, reports the results, and reviews some prominent theoretical models for elastic scattering in light of existing data at WA7 energies and above. The results presented here have previously been reported in the form of letters [1-5]. In an earlier phase of the WA7 experimental programme, elastic hadron scattering at very large momentum transfers was measured at 20 and 30 GeV/c [6].

Results for $\bar{p}p$ two-body annihilation into $\pi^-\pi^+$ and K^-K^+ at 30 and 50 GeV/c, which were measured in parallel with the elastic $\bar{p}p$ cross sections, are also presented.

While the pp 50 GeV/c data complement existing pp data, which cover a wide range of energies and momentum transfers [7-11], the $\bar{p}p$, πp and Kp measurements probe s- and t-regimes which were largely unexplored prior to this experiment. Elastic $\bar{p}p$ data above 10 GeV/c were limited to $|t| < 1.3$ (GeV/c)² [12-14]², while lower energy data reached higher $|t|$ -values [15-17]. The $\bar{p}p$ elastic differential cross section has recently been measured in the non-forward region at 100 and 200 GeV/c [9] and at $\sqrt{s}=546$ GeV [18]. Compared with proton-proton data, medium- $|t|$ meson-proton data are very limited. The large- $|t|$ πp and Kp data of Baglin et al. [6] do not cover the

² Upper limits for the $\bar{p}p$ elastic differential cross sections at 20 and 30 GeV/c at very large $|t|$ had been established by Baglin et al. [6].

region below $|t| \approx 6 \text{ (GeV/c)}^2$. Until recently, π^-p data covering the medium- $|t|$ region up to $|t| \approx 5 \text{ (GeV/c)}^2$ only reached a momentum of 23 GeV/c [19,20]; πp data above 50 GeV/c did not extend beyond $|t| \approx 2 \text{ (GeV/c)}^2$ [21]. $\pi^\pm p$ data have now become available at 100 and 200 GeV/c [22]. However, only the π^-p 200 GeV/c data extend beyond $|t| \approx 3.5 \text{ (GeV/c)}^2$. Kp data are even more scarce; data reaching $|t| \approx 5 \text{ (GeV/c)}^2$ only exist for momenta up to $\sim 10 \text{ GeV/c}$ [19]. The recent $K^\pm p$ data at 100 and 200 GeV/c [22] cover the region up to $|t| \approx 2.5 \text{ (GeV/c)}^2$.

There is at present no coherent and fundamental description of elastic scattering processes. The dominant theory of strong interactions, QCD, remains largely excluded from the field of elastic hadron scattering. Of course, this is true for all low- p_t (soft) processes. Some attempts have been made to obtain lowest order QCD predictions for the s - and t -dependence of large-momentum-transfer exclusive processes [23]. While there are indications that these predictions may be consistent with the large- $|t|$ behaviour of pp data [24], there is considerable uncertainty about their agreement with πp data (see ref.[24] and section 4.1.4). Comprehensive descriptions of elastic scattering, covering both forward and non-forward scattering, are left to more phenomenological models. In the forward direction, analyticity effectively constrains the properties of the elastic amplitude. In the past, Regge-pole analysis was widely applied in the forward direction, but it is now less appealing as a result of the rapid increase of the total cross section [25]. A more serious problem is that Regge phenomenology lacks a basis in a fundamental theory of strong interactions like QCD.

Several phenomenological models have been suggested to describe non-forward elastic scattering. The theoretical situation is rather confusing,

since the models are rooted in very different physical pictures. Effective constraints can only be provided by data. The observation of a dip in the pp cross sections at the ISR prompted a major theoretical investigation into the dip-producing mechanism. Surprisingly, most models have been able to describe, quantitatively or qualitatively, the shape and the movement of the dip [26-30]. The situation clearly calls for more data to enable the different models to be critically evaluated, as well as further developed.

The WA7 experiment, which employed a dedicated medium- t set-up covering the region $0.5 < |t| < 10 \text{ (GeV/c)}^2$, was a modified version of the large-angle set-up described in ref.[6]. Data taking fell into two periods. The meson-proton data and the $\bar{p}p$ 50 GeV/c data were recorded in Period-I, while the $\bar{p}p$ 30 GeV/c and pp 50 GeV/c data were taken in Period-II. The set-up was upgraded and slightly changed between the two periods.

The following differential cross sections were measured:

Elastic (Period-I)

$\pi^-p \rightarrow \pi^-p$	20 GeV/c	$0.6 < t < 6.5 \text{ (GeV/c)}^2$
$\pi^-p \rightarrow \pi^-p$	50 GeV/c	$0.7 < t < 8.0 \text{ (GeV/c)}^2$
$\pi^+p \rightarrow \pi^+p$	50 GeV/c	$0.7 < t < 8.0 \text{ (GeV/c)}^2$

$K^-p \rightarrow K^-p$	20 GeV/c	$0.6 < t < 4.5 \text{ (GeV/c)}^2$
$K^+p \rightarrow K^+p$	50 GeV/c	$0.7 < t < 8.0 \text{ (GeV/c)}^2$

$\bar{p}p \rightarrow \bar{p}p$	50 GeV/c	$0.7 < t < 5.0 \text{ (GeV/c)}^2$
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Elastic (Period-II)

$\bar{p}p \rightarrow \bar{p}p$	30 GeV/c	$0.5 < t < 5.8 \text{ (GeV/c)}^2$
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$$pp \rightarrow pp \quad 50 \text{ GeV}/c \quad 0.8 < |t| < 4.0 \text{ (GeV}/c)^2$$

Annihilation (Period-I)

$$\bar{p}p \rightarrow \pi^-\pi^+ \quad 50 \text{ GeV}/c \quad 2.0 < |t| < 4.0 \text{ (GeV}/c)^2 \quad (\text{upper limits})$$

$$\bar{p}p \rightarrow K^-K^+ \quad 50 \text{ GeV}/c \quad 2.0 < |t| < 4.0 \text{ (GeV}/c)^2 \quad (\text{upper limits})$$

Annihilation (Period-II)

$$\bar{p}p \rightarrow \pi^-\pi^+ \quad 30 \text{ GeV}/c \quad 2.0 < |t| < 4.0 \text{ (GeV}/c)^2 \quad (\text{upper limits})$$

$$\bar{p}p \rightarrow K^-K^+ \quad 30 \text{ GeV}/c \quad 2.0 < |t| < 4.0 \text{ (GeV}/c)^2 \quad (\text{upper limits})$$

Part 2 reviews the experimental set-up and trigger logic of Period-II, and briefly describes how the Period-I set-up differed. Part 3 describes the data analysis in Period-II, and also summarizes special characteristics of the Period-I data analysis. The differential cross sections are presented in part 4. The presentation is followed by a discussion in which relevant theoretical models are reviewed and confronted with data. Meson-proton data and (anti)proton-proton data are treated separately. Conclusions are drawn in part 5.

2. EXPERIMENTAL SET-UP AND TRIGGER LOGIC

A description of the set-up and trigger logic for the 30 GeV/c $\bar{p}p$ and 50 GeV/c pp runs (Period-II) is given. A brief description of how Period-I differed is given in section 2.5.

2.1 GENERAL LAY-OUT

The experimental set-up, shown schematically in Fig.1, consisted of two detector arms downstream of a liquid hydrogen target. The beam particles were detected by a beam hodoscope, while identification was provided by two differential Cerenkov counters (CEDARs). The scattered particles were detected by counter hodoscopes and Multi-Wire Proportional Chambers (MWPC) in the forward and recoil arms, while identification was provided by two threshold Cerenkov counters in the forward arm. The momentum and the energy of the forward scattered particles were determined with a spectrometer magnet and a hadron calorimeter, respectively.

2.2 BEAM-LINE AND TARGET

A secondary, unseparated beam (E1B/H1B) in the SPS West Experimental Area was used. Electrons in the beam were effectively absorbed by a lead absorber far upstream. The μ -content was estimated to be $\sim 5\%$, and the hadronic content was measured to be $\pi^-/\bar{p}/K^- \approx 0.94/0.03/0.03$ at -30 GeV/c, and $\pi^+/p/K^+ \approx 0.58/0.38/0.04$ at $+50$ GeV/c, using the beam hodoscope and the CEDARs. The beam intensity was, typically, $1-2 \times 10^7$ ppb, with a burst duration of ~ 1 second every 10 seconds.

The position of an incoming beam particle was provided by the beam hodoscope (BH), composed of three planes with 40 scintillator strips each. The strips were $2.2 \times 5 \times 100$ mm³ large, overlapped by 0.1mm, and were arranged in 2 rows of 20 elements. The three planes were mounted vertically and at $\pm 45^\circ$ to the vertical. The spatial resolution of the beam hodoscope was 2mm.

The beam hodoscope was also used for beam intensity measurement. An ionization chamber further upstream served as an independent intensity monitor, and was used to check for saturation of the beam hodoscope counts at high rates. No saturation effect was observed in the beam hodoscope for intensities up to 3×10^7 ppb.

Of the two CEDARs used for identifying beam particles, CEDAR1 (CD1) tagged protons ($\bar{p}$), while CEDAR2 (CD2) tagged kaons at -30 GeV/c. A third CEDAR (CD3), tagging antiprotons, was located in the beam line downstream of the target. This was used to identify simulated antiproton events, in which a pion accompanied an incident antiproton within the resolution time of the apparatus, scattered, and failed to fire the forward Cerenkov counters. CD3 was not used during the 50 GeV/c pp measurements.

The target was liquid hydrogen contained in a 1m long mylar cylinder with a radius of 4cm . Surrounding scintillation counters were used to veto multi-particle events with tracks partly outside the geometrical acceptance of the experiment.

2.3 SET-UP DOWNSTREAM OF TARGET

2.3.1 Counter Hodoscopes

The scintillation counter hodoscopes H1, PR1 in the forward arm and H2, PR2 in the recoil arm detected scattered particles. The hodoscope signals constituted the input to the trigger logic which checked the geometry of the events.

H1, situated immediately downstream of the magnet, consisted of 12 ring elements, each 5cm wide. Each ring was divided into an upper and a lower half in order to reduce the jitter. The rings simulated a polar coordinate structure which was suitable for the trigger logic. H2, placed alongside the target, contained 10 vertically mounted elements, each 5×28 or $12 \times 28 \text{ cm}^2$.

The two downstream prompt-hodoscopes PR1 and PR2 had a time resolution of approximately 0.5 nsec. PR1 consisted of 48 counter elements, each 15×15 , 15×30 or $30 \times 30 \text{ cm}^2$. The elements were arranged in a configuration of 8 "rings", which facilitated correlations with the H1 rings. PR2 contained 12 elements, each $30 \times 30 \text{ cm}^2$, which were organized in a 3×4 matrix configuration.

A more detailed description of the counter hodoscopes is given in ref.[6].

2.3.2 Multi Wire Proportional Chambers (MWPC)

Tracking of the scattered particles was provided by 9 MWPCs with a total of 35 wire planes. There were 6 MWPCs in the forward arm (CH0-CH5) and 3 MWPCs in the recoil arm (CH7-CH9). Off-line reconstruction of the tracks was based on MWPC digitizings.

MWPCs in the forward arm each contained from 3 to 6 wire planes. The wire orientation was partly vertical and horizontal (X,Y), partly rotated (U,V)³, thereby reducing the number of ambiguities caused by multiple clusters. Wire spacing was 1, 2 or 4mm. CH5 was rotated 45° to maximize the geometrical acceptance.

³ V,U rotational angles were $\pm \arctan(8/15)$ relative to the horizontal X-axis.

Each recoil MWPC contained 3 wire planes with wire orientations X,Y, and U or V. The wire spacing was 2mm.

Table 1 summarizes the MWPC characteristics. Each wire inside the geometrical acceptance of the set-up corresponded to one read-out (R/O) channel. Total number of R/O channels was 18304.

2.3.3 The Spectrometer Magnet

The field volume of the magnet was $1.5 \times 0.75 \times 1.5 \text{ m}^3$. With a current of 5000A, the vertical field component at the centre of the magnet was 1.2T, and the field integral along the z-axis was 1.8Tm. Polarity was switched between the -30 and +50 GeV/c runs, so that the scattered beam particles were always bent towards the beam axis. The momentum of the forward particles was determined off-line with a precision of $\pm 10\%$ and $\pm 15\%$ for -30 GeV/c and +50 GeV/c incident beams, respectively.

2.3.4 Cerenkov Counters

Two threshold Cerenkov counters in the forward arm (C1,C2) identified the scattered particles. Cerenkov information was available at the second trigger level. The gas fillings were at atmospheric pressure, and were selected to give suitable momentum thresholds. The characteristics of C1 and C2 are given in Table 2.

2.3.5 The Calorimeter

An iron calorimeter, situated at the end of the forward arm, allowed the energy of fast particles to be measured. It consisted of iron plates ($200 \times 200 \times 10 \text{ cm}^3$) and 6 scintillator planes in a sandwich configuration. A scintillator plane consisted of 20 to 32 counters, each $100 \times 12.5 \times 2$, $100 \times 25 \times 2$ or $100 \times 30 \times 2 \text{ cm}^3$. The sum of the voltage amplitudes from each counter was proportional to the energy deposited. A pulse height threshold corresponding to a conservative energy cut was selected, and the discriminated signal (CAL) was used at the second trigger level.

2.4 TRIGGER LOGIC AND DATA ACQUISITION

The trigger was divided into two levels in order to minimize dead time. The first level implemented a fast logic which did a rough check on the event geometry. The second level performed a more accurate check on the event geometry, and incorporated target and multiplicity vetoes as well as CEDAR and calorimeter information.

2.4.1 First Trigger Level

The first, preliminary selection of event candidates was performed by a fast trigger logic ($\tau \approx 20 \text{ nsec}$), which did a rough check on the event geometry as defined by the counter hodoscopes. Counter hodoscope elements were first ORed together into "rings" (or columns). The ORed signals entered four programmable fast matrix coincidence units. The matrices defined ring coincidence combinations which required approximately straight line track

segments pointing at the target in each spectrometer arm, and opening angles consistent with elastic kinematics. A fast STROBE signal was defined by the coincidences

$$\text{STROBE} \equiv (\text{PR1R} * \text{H1R}) * (\text{PR2R} * \text{H2R}) * (\text{H1R} * \text{H2R}) * (\text{PR1R} * \text{PR2R})$$

(R = ring element). The strobe latched counter information into CAMAC registers and MWPC information into Read Memory Hybrid (RMH) modules. The strobe was inhibited for 300nsec to allow the second trigger level to reach a decision. At a beam intensity of 1.5×10^7 ppb, the STROBE rate was, typically, 1.5×10^5 per burst.

2.4.2 Second Trigger Level

The slow logic did a more sophisticated check on the event geometry by correlating individual prompt hodoscope elements. Individual signals were input to a 48x48 programmable "slow" matrix which checked PR1*PR2 single element coincidences according to elastic kinematics.

At least one hit in each of the four counter hodoscopes was required. Hodoscope multiplicity constraints were introduced in the trigger at this stage to reject high-multiplicity events. This logic vetoed events with $\text{H1} \geq 3$ OR $\text{PR1} \geq 3$ OR $\text{H2} \geq 3$ OR $\text{PR2} \geq 3$. The target veto information also entered the trigger at this level. A "CANDIDATE" (CAND) trigger signal was generated by the coincidences

$$\text{CAND} \equiv (\text{slow matrix}) * \overline{(\text{multiplicity veto})} * \overline{(\text{target veto})}$$

Cerenkov and calorimeter information finally entered the logic to generate particle "EVENTS" according to the signatures

-30 GeV/c $\bar{p}$ -EVENT $\equiv$ STROBE * CAND * CD1 * CAL

-30 GeV/c K-EVENT $\equiv$ STROBE * CAND * CD2 * C2 * CAL

+50 GeV/c p-EVENT $\equiv$ STROBE * CAND * CD1 * CAL

(p-trigger only).

An EVENT signal generated an interrupt to the on-line computer, which recorded the event. If the slow logic did not generate an EVENT signal within 300nsec of the original strobe, the CAMAC and RMH registers were reset. There were typically 20 $\bar{p}$ -EVENTS (~100 p-EVENTS) per burst.

2.4.3 Data Acquisition System

The experiment used a NORD-10 on-line computer with 196K of 16-bit memory, two magnetic tape units, and a 9M-byte disc system.

Standard CAMAC and the CERN-designed Read Memory Hybrid (RMH) system constituted the data acquisition system. The CAMAC registers stored information from the scintillation counters, CEDARs and Cerenkov counters. MWPC information was recorded by the RMH system.

The read-out time from CAMAC and RMH was ~4msec, and was the dominant contribution to the dead-time.

2.5 SET-UP AND TRIGGER LOGIC IN PERIOD-I

Special characteristics of the experimental set-up and trigger logic for the π^-p/K^-p 20 GeV/c, $\pi^-p/\bar{p}p$ 50 GeV/c, and π^+p/K^+p 50 GeV/c runs (Period-I) are outlined below. (A detailed description of this period is given in ref.[31]).

2.5.1 Set-up

The main differences from the Period-II set-up were as follows:

- a) A high-yield threshold Cerenkov counter (CP1) was used in place of a second CEDAR because of limited space in the beam line. It was filled with neon at atmospheric pressure. The thresholds were the same for all incident momenta (Table 3). CP1 was included in the π -trigger at ± 50 GeV/c.
- b) Three "prompt veto" counters situated immediately downstream of the target completed the target veto box.
- c) There were 6 MWPC modules in the forward arm with a total of 26 wire-planes (X,Y,U/V). The recoil arm included 4 MWPCs with 3 wire-planes each (X,Y,U/V).
- d) The appropriate Cerenkov thresholds are given in Table 4.
- e) The calorimeter, an early version of that used in Period-II, contained only two scintillator planes. It was introduced in the trigger in the final -20 GeV/c runs, and remained in the trigger in the subsequent ± 50 GeV/c runs.

f) The counter hodoscope H1 consisted of 14 ring elements of 5cm width, while H2 contained 8 vertically mounted counter elements (5×28 or $12 \times 28 \text{ cm}^2$). H2 was situated directly in front of the first MWPC in the recoil arm, separated from it by a silica aerogel Cerenkov counter (see g)). The 48 rectangular elements of PR1 were arranged in 10 "rings". PR2 contained 8 counter elements, each $32 \times 30 \text{ cm}^2$, organized in a 2×4 matrix configuration.

g) A silica aerogel threshold Cerenkov counter (C5) was located in the recoil arm immediately behind H2. Providing π/p separation in the momentum range $1 < p_p < 4 \text{ GeV}/c$ (corresponding to $1 < |t| < 6 \text{ (GeV}/c)^2$ at WA7 energies), it was introduced in the π -trigger at $\pm 50 \text{ GeV}/c$ to veto low- $|t|$ events with a pion in the recoil arm (see next section).

2.5.2 Trigger Logic

The trigger in Period-I differed from that of Period-II at

a) the first trigger level, which also included the target "prompt veto":

$$\text{STROBE} \equiv (\text{PR1R} * \text{H1R}) * (\text{PR2R} * \text{H2R}) * (\text{H1R} * \text{H2R}) * (\text{PR1R} * \text{PR2R}) * \overline{(\text{prompt veto})},$$

and

b) the second trigger level, at which the slow matrix also checked the correlation $\text{PR1}_{\text{single}} * (\text{H2R} * \text{PR2R})$.

The final EVENT signatures were:

-20 GeV/c π -EVENT $\equiv$ STROBE * CAND * C1 * C2 (* CAL)⁴

" K-EVENT $\equiv$ STROBE * CAND * CD1 * C2 (* CAL)⁴

-50 GeV/c π -EVENT $\equiv$ STROBE * CAND (* C1)⁵ * C2 (* (C5-veto))⁵ * CAL

" $\bar{p}$ -EVENT $\equiv$ STROBE * CAND * CD1 * CAL

+50 GeV/c π -EVENT $\equiv$ STROBE * CAND * CP1 * C2 * (C5-veto) * CAL

" K-EVENT $\equiv$ STROBE * CAND * CD1 * C2 * CAL

C5 vetoed events with a pion in the recoil arm ("background"). The veto was, however, only active for low- $|t|$ events, which were defined by PR1 and H1 coincidences:

$C5\text{-veto} \equiv C5 * [(PR1, ring1+2+3)*H1R]$.

This restriction was imposed in order to avoid accidental vetoes of recoiling protons above $|t| \approx 6 \text{ (GeV/c)}^2$, where C5 did not distinguish between pions and protons.

⁴ Calorimeter introduced in final runs.

⁵ C1 and C5-veto only in second part of the run.

3. DATA ANALYSIS

A description of the analysis of the 30 GeV/c $\bar{p}p$ and 50 GeV/c pp data (Period-II) is given. The analysis of Period-I data differed mainly in the final event selection and in parts of the normalization. These differences are briefly described in section 3.4.

3.1 EVENT RECONSTRUCTION, DATA REDUCTION AND KINEMATIC FITTING

The number of raw data events reaching the reconstruction routines was reduced at an early stage in the analysis by rejecting "bad" events which could not be properly decoded. In addition, disallowed combinations of $PR1_{\text{single}}*(H2R*PR2R)$ were rejected. This rejection, simulating an extended slow matrix, was typically ~15%.

To reconstruct events, pattern recognition procedures were applied on the MWPC digitizings in the two arms. In order to simplify the pattern recognition, roads were defined by the fired counter hodoscope elements. Only MWPC digitizings within the roads were considered.

Track finding started downstream of the magnetic field. Straight lines were fitted to the MWPC clusters, requiring a minimum number of digitizings. Acceptable lines were extended through the magnetic field into CH0-CH2. The roads in CH0-CH2 were found by a Monte Carlo calculation of the curved particle trajectories in the magnetic field. Once an acceptable track had been found, a first approximation to the momentum was calculated. Next, straight lines in the recoil arm were reconstructed.

The 2-prong vertex was defined as the midpoint on the shortest distance between the forward and recoil tracks. This distance was required to be less than 3cm.

Beam tracks were reconstructed from the fired beam hodoscope elements, assuming zero beam divergence. The reconstructed beam tracks were then checked against the 2-prong vertices. The square of the distance from the 2-prong vertex to the closest beam track (3-prong vertex parameter) was required to be less than 3cm^2 . A 3-prong vertex was defined to lie on this line $1/3$ of the distance away from the 2-prong vertex.

Vertices were required to be located within the target. To eliminate obviously inelastic vertices from the sample to be fitted, conservative cuts were imposed on the forward momentum, the scattering angles, the coplanarity, and the quantity $\Delta\theta$, where $\Delta\theta$ is the difference between the measured forward scattering angle and the one expected for an elastic event given the measured recoil scattering angle.

A kinematic fit with an elastic hypothesis was made to all remaining event candidates. Input to the fit consisted of the beam track, the MWPC digitizings in CH0-CH2, and the forward and recoil straight lines. If no beam track had been reconstructed (2-prong vertex), a nominal beam position and direction was used. The particle trajectory in the magnetic field was computed using Runge-Kutta numerical integration [32]. Conservation of four-momentum was imposed on the vertex. The χ^2 from the least squares fit was the main selection criterion for elastic events. Since the number of MWPC digitizings varied, the number of degrees of freedom (dof) varied between 8 and 14, with a mean value of 12.

About 1.9×10^6 -30 GeV/c triggers and 6.1×10^5 $+50$ GeV/c triggers were analysed, of which $\sim 88\%$ were rejected during the event reconstruction and the preceding data reduction. Of the remainder, $\sim 37\%$ and $\sim 55\%$ (-30 and $+50$ GeV/c) were rejected by the kinematic cuts and during fitting. Total event rejection at this stage was thus $\sim 92\%$ and $\sim 94\%$.

3.2 EVENT SELECTION AND BACKGROUND SUBTRACTION

Each event usually had several fitted vertices. To obtain a clean and homogenous data sample, 2-prong vertices were first rejected. The 3-prong vertex with the smallest χ^2/dof was then selected (hereafter called (best) "event"). For final event selection, the particle signatures were inspected. $\bar{p}p$ and pp events were required to have the following signatures (-30 and $+50$ GeV/c):

$\bar{p}(p)$ -EVENT

CD1

$\overline{C1} * \overline{C2}$

During -30 GeV/c data taking, CEDAR3 was tuned to antiprotons. An additional requirement for $\bar{p}p$ -events was $\overline{CD3}$.

K-events have not been extracted from the -30 GeV/c data.

The χ^2/dof distributions for selected $\bar{p}p$ and pp events are shown in Fig.2a,b for three different t-bins. Clear elastic signals are seen, except in the $\bar{p}p$ dip region. The distributions clearly reveal the $\bar{p}p$ 30 GeV/c dip-bump structure and the pp 50 GeV/c shoulder.

In order to estimate the background underneath the elastic signals, a set of χ^2/dof cuts were imposed (arrows in Fig.2). The selected cuts took into account an observed broadening of the χ^2/dof distributions at low $|t|$. Monte Carlo simulations showed that this effect was mainly due to multiple scattering of the low-momentum recoiling protons. About 45% (12429 events) of the selected $\bar{p}p$ -events and ~16% (2303 events) of the selected pp events survived the χ^2/dof cuts. The background was then extrapolated from above the cut, assuming a square root χ^2/dof distribution passing through the origin [33]⁶. The observed deviation from a square root shape at high χ^2/dof was attributed to the effect of the kinematic cuts. The dashed curves in Fig.2 represent the square root fits to the background. Depending on t -bin, the estimated background amounted to 3-20% of all $\bar{p}p$ -events below the cut, with the exception of the dip region ($1.5 < |t| < 1.8$) where it was about 50%. For pp -events, the background was less than 10% at the lowest $|t|$ -values, rising to a maximum of ~30% around $|t|=1.4$ (GeV/c)². Subtracting the background below the cut yielded the number of elastic events. A total of 11870 elastic $\bar{p}p$ 30 GeV/c events ($\approx 0.6\%$ of the raw data events) and 1995 elastic pp 50 GeV/c events ($\approx 0.3\%$ of the raw data events) were extracted.

⁶ The square root shape of the background distribution was suggested by the data. However, this distribution has also some theoretical justification, since it is the background shape expected in a least squares fit with 3 constraints [33]. Our fit had both geometrical and kinematic constraints, but presumably the background events were of a kind that satisfied the geometrical constraints. Moreover, of the 4 kinematic constraints, only 3 were effective, because the recoil momentum was not measured.

The coplanarity and $\Delta\theta$ distributions for events below the χ^2/dof cut are shown in Fig.3a,b (solid lines) for pp 50 GeV/c, $1.0 < |t| < 1.1 \text{ (GeV/c)}^2$. Clear elastic signals, centered roughly around zero, are seen above a low "background". No elastic signals are observed in a χ^2/dof range immediately above the cut (cut→cut+8), as illustrated by the dotted curves in Fig.3a,b. These curves indicate that the background is distributed over a wide range in coplanarity and $\Delta\theta$, although it tends to peak around zero.

3.3 NORMALIZATION

Two groups of corrections, t-dependent and t-independent, were calculated. All correction factors were applied to the lifetime-gated beam particle flux, measured by CEDAR1 to $\sim 1.5 \times 10^{10}$ antiprotons and $\sim 8 \times 10^9$ protons.

t-dependent corrections:

i) Acceptance

The geometrical acceptance of the experiment, including the trigger matrix acceptance, was calculated by a Monte Carlo simulation of elastic events. Fig.4 (solid curve) shows the elastic acceptance as a function of $|t|$ for -30 GeV/c incident antiproton beam.

ii) Reconstruction Efficiency

Elastic events could fail to be reconstructed because of MWPC inefficiencies. To correct for this loss, the reconstruction efficiency was calculated from the sample of selected events, applying the reconstruction criteria of the pattern recognition. The angular efficiency distribution did not exhibit significant

structure; it dropped smoothly from $\approx 80\%$ around $|t|=0.7 \text{ (GeV/c)}^2$ to a plateau around 70% at higher $|t|$ values, at both -30 and $+50 \text{ GeV/c}$.

iii) Target Absorption

Inelastic absorption in the target reduced the effective beam flux. The loss of elastic events depended on the elastic vertex distribution in the target. This exhibited a shift towards the downstream end of the target with decreasing $|t|$ (an acceptance effect), and hence the absorption correction was largest at small $|t|$. The 30 GeV/c antiproton flux was corrected for an average absorption of $\sim 11\%$ at low $|t|$ and $\sim 9\%$ at high $|t|$. Corresponding corrections for the 50 GeV/c proton flux were 9% and 8% .

t-independent corrections:

i) Beam Hodoscope Efficiency

Only 3-prong events were accepted in the event selection. It was therefore necessary to correct for the loss of elastic events due to beam hodoscope inefficiencies. Studying the beam hodoscope information per plane for a large sample of reconstructed events, the combined efficiency for the three planes was calculated to be $\sim 90\%$ at -30 GeV/c and $\sim 87.5\%$ at $+50 \text{ GeV/c}$.

ii) Beam Hodoscope Interactions

The incident protons were tagged by CEDAR1, which was situated upstream of the beam hodoscope. Beam particle interactions in the beam hodoscope reduced the effective flux of incident protons ($\bar{p}$) on the target by an estimated 2% at both -30 and $+50 \text{ GeV/c}$.

iii) Random Multiplicity Veto

The multiplicity constraints on the counter hodoscopes reduced the trigger rate by roughly a factor 100. However, the constraints also introduced accidental, random multiplicity vetoes of elastic events which were accompanied by high multiplicity interactions between the beam halo and the experimental surroundings. The random veto depended on the beam intensity, and was expected to be negligible at low intensities. The average event loss due to random multiplicity vetoes was calculated to about 15% at -30 GeV/c and 14% at +50 GeV/c.

iv) Calorimeter Loss

The statistical fluctuations in the pulse heights from the calorimeter gave a loss of elastic events estimated to be about 22% at -30 GeV/c and 20% at +50 GeV/c. The correction was calculated from special calibration runs with no calorimeter in the trigger.

The dominant contributions to the errors in the differential cross sections were the statistical uncertainty in the estimated number of elastic events (2-100% at -30 GeV/c, 4-50% at +50 GeV/c), and the systematic uncertainty in the background subtraction (2-20%). The overall systematic normalization uncertainty is estimated to be $\pm 15\%$.

The overall normalization was checked by comparing our pp 50 GeV/c differential cross section with existing small- $|t|$ pp 50 GeV/c data from Akerlof et al.[21] (Fig.17). The agreement was found to be well within the statistical and systematic errors of the two experiments.

3.4 DATA ANALYSIS IN PERIOD-I

Special characteristics of the π^-p/K^-p 20 GeV/c, $\pi^-p/\bar{p}p$ 50 GeV/c, and π^+p/K^+p 50 GeV/c (Period-I) data analysis are given below. (A detailed description of the data analysis for this period is given in ref. [31]).

3.4.1 Event Selection and Background Subtraction

The required particle signatures were:

-20 GeV/c π^-p : π -EVENT
C1 * C2

" K^-p : K-EVENT
CD1
 $\overline{CP1}$
 $\overline{C1} * C2$
1 reconstructed beam track

-50 GeV/c π^-p : π -EVENT
(C1 *)⁷ C2

" $\bar{p}p$: $\bar{p}$ -EVENT
CD1
 $\overline{C1} * \overline{C2}$

⁷ C1 only in second part of the run.

```

+50 GeV/c   $\pi^+p$ :   $\pi$ -EVENT
                   $\overline{CD1}$ 
                  CP1
                  C1 * C2

"            $K^+p$ :  K-EVENT
                  CD1
                  C1 * C2

```

Fig.5 shows the χ^2 -distributions for selected $\bar{p}p$ events at 50 GeV/c for three different t -bins. The dip-bump structure is clearly revealed.

After imposing t -dependent χ^2 -cuts, the background distribution was extrapolated smoothly to low χ^2 , being constrained to pass through the origin. Alternatively, the distribution above the cut was fitted to a polynomial function of χ^2 and extrapolated below the cut. The two approaches gave consistent results within $\sim 6\%$ (~ 20 GeV/c). A consistency check at low $|t|$ was provided by the coplanarity distributions, in which the background was fitted either by a gaussian distribution or by eye. Background subtraction in high- $|t|$ bins was based solely on the χ^2 -distributions.

3.4.2 Normalization

The Period-I set-up, trigger and data analysis program introduced the following correction factors not required for Period-II:

i) πp and Kp corrections (the quoted values refer to $-20 \text{ GeV}/c$):

Cerenkov signals in the forward arm were required for πp and Kp event identification. For these reactions, the angular Cerenkov efficiencies of C1*C2 or C2 were applied as corrections to the angular event distributions. C2 had a high, uniform efficiency of $\sim 99\%$, while the C1-efficiency deteriorated at low $|t|$, dropping below 50% for $|t| < 1(\text{GeV}/c)^2$.

The flux of incident pions was measured by the beam hodoscope. The correction to the measured π -flux for the μ, K and p content of the beam was around 9%. The flux was also corrected for a beam hodoscope overcount of $\sim 24\%$, caused by high multiplicity interactions in the upstream CEDAR, δ -rays, and overlapping hodoscope elements. Since the beam hodoscope counted continuously (burst gated) in the $-20 \text{ GeV}/c$ run, the π -flux was multiplied by the livetime (0.67).

Pions accompanying kaons and scattering elastically could simulate K -events by failing to fire C1 ($-20 \text{ GeV}/c$). Pion contamination in the K^-p $20 \text{ GeV}/c$ event sample was reduced to $\sim 0.3\%$ by selecting K -events with only one reconstructed beam track, and by checking CP1 which counted pions. However, $\sim 33\%$ of the incident kaons were rejected by imposing the single-beam-track requirement. A correction factor of 0.67 was therefore applied to the $-20 \text{ GeV}/c$ K -flux.

ii) $\bar{p}p$ corrections:

In the first part of the $-50 \text{ GeV}/c$ run, C1 did not cover the low- $|t|$ region. This enabled a pion, which accompanied an $\bar{p}$ and scattered elastically, to simulate an $\bar{p}$ -event by failing to fire C2. The $\bar{p}p$ $50 \text{ GeV}/c$ cross section was therefore corrected for a low- $|t|$ π -contamination of up to 10%.

iii) General corrections (quoted values refer to $-20 \text{ GeV}/c$):

δ -rays, produced in the target and firing the nearby prompt-veto counters, vetoed an estimated 12% of the elastic events.

Inefficient zones in the counter hodoscope elements gave an event loss estimated at 6%.

The flux was corrected for a 10% loss of elastic events in the off-line track reconstruction routine.

The 3-prong vertex parameter (section 3.1) was required to be less than 1cm^2 , thereby rejecting an estimated 2% of the elastic events.

The systematic normalization uncertainty was estimated to be $\pm 15\%$.

3.5 ANNIHILATION ANALYSIS

The $\bar{p}$ -triggers at 30 and 50 GeV/c also accepted the two-body annihilation events $\bar{p}p \rightarrow \pi^- \pi^+$ and $\bar{p}p \rightarrow K^- K^+$. Separate fits with the two annihilation hypotheses were therefore made to the reconstructed $\bar{p}p$ events with the annihilation signature:

$\bar{p}$ -EVENT

CD1

C1 + C2

Only 3-prong events, having reconstructed beam tracks, were considered. At -30 GeV/c, C2 was required, while at -50 GeV/c a C1*C2 coincidence was required. From the χ^2/dof distributions, no clear signals were seen. We then applied a χ^2/dof cut at 2.4, and, as for the elastic case, a square root χ^2/dof distribution of the background (see section 3.2). The resulting distributions showed no signals, with the exception of annihilation into $\pi^-\pi^+$ at -50 GeV/c, where a small signal of 2.5 ± 2.6 events appeared out of 7 events below the cut. However, treating the sample statistically, and taking into account the large uncertainties involved, we are only able to give upper limits for the differential cross sections.

The normalization of the differential cross sections was the same as for the elastic $\bar{p}p$ data, with the following exceptions:

- a) The geometrical acceptance was calculated for the two annihilation channels (Fig.4). At lower $|t|$ -values, this was drastically smaller than the elastic acceptance. In particular, there was practically no $\pi\pi$ -acceptance below $|t| \approx 2 \text{ (GeV/c)}^2$ at -30 GeV/c.
- b) The overall Cerenkov efficiencies (C1*C2 at 50 GeV/c, C2 at 30 GeV/c) were applied as correction factors.

The systematic normalization uncertainty was estimated to be $\pm 15\%$.

4. RESULTS AND DISCUSSION

The elastic differential cross sections are listed in Tables 5-12. Upper limits for the differential cross sections of $\bar{p}p$ two-body annihilation into $\pi^-\pi^+$ and K^-K^+ are listed in Tables 13-16.

4.1 πp AND Kp ELASTIC SCATTERING

The π^-p 20 GeV/c elastic differential cross section (Table 5) is shown in Fig.6 together with large- $|t|$ ($|t| > 7$ (GeV/c)²) 20 GeV/c data from the earlier large-angle phase of this experiment [6], and lower energy π^-p data at 9.7 GeV/c [19]. The 20 GeV/c cross section shows a diffraction peak which falls exponentially between $0.6 < |t| < 2.5$ (GeV/c)² over roughly four orders of magnitude. A minor change of slope is observed around $|t| = 1$ (GeV/c)²; parametrizing $d\sigma/dt$ as $A \exp(Bt)$ on each side of the break point, B changes from 6.2 ± 0.5 to 4.8 ± 0.2 (GeV/c)⁻². At lower momenta ($p_{lab} < 4$ GeV/c), an appreciable dip is seen around $|t| = 1$ (GeV/c)² [34]. A much more dramatic change of slope is seen around $|t| = 2.8$ (GeV/c)², followed by a shoulder with a very shallow dip. The low-energy dip around $|t| = 2.8$ (GeV/c)² (Fig.6) has thus been partly filled at 20 GeV/c, confirming the data of Cornillon et al. at 22.6 GeV/c [20]. The large- $|t|$ region ($|t| > 5$ (GeV/c)²) can be approximated by a Constituent Interchange Model (CIM) fit [6] with a t -dependence close to $|t|^{-4}$ (Fig.6) (an alternative interpretation of the cross section in this region is discussed in section 4.1.4).

The π^-p 50 GeV/c elastic differential cross section (Table 6), shown in Fig.7, falls exponentially between $0.7 < |t| < 3.0$ (GeV/c)², decreasing by five

orders of magnitude. Around $|t|=1.6 \text{ (GeV/c)}^2$ the slope parameter B changes from 5.3 ± 0.2 to $4.7 \pm 0.2 \text{ (GeV/c)}^{-2}$. A pronounced change of slope is seen around $|t|=3 \text{ (GeV/c)}^2$, followed by a less steep fall-off. The lower energy dip around $|t|=2.8 \text{ (GeV/c)}^2$ is seen to have been totally suppressed at 50 GeV/c. The large- $|t|$ ($|t| > 5 \text{ (GeV/c)}^2$) behaviour of the differential cross section is consistent with a $|t|^{-3}$ dependence (see section 4.1.4).

The π^+p 50 GeV/c elastic differential cross section (Table 7), illustrated in Fig.8, again falls exponentially between $0.7 < |t| < 2.8 \text{ (GeV/c)}^2$. The slope parameter B is $4.6 \pm 0.2 \text{ (GeV/c)}^{-2}$, slightly smaller than the π^-p 50 GeV/c parameter. A small dip is observed around $|t|=3.8 \text{ (GeV/c)}^2$. Beyond the dip, the π^+p cross section seems to fall off faster than the π^-p cross section at the same momentum; the region $|t| > 5 \text{ (GeV/c)}^2$ can be described by a $|t|^{-7}$ dependence (Fig.8).

In Fig.9 the π^-p 20 and 50 GeV/c data are compared with existing π^-p data at 200 GeV/c from Fermilab [22]. The latter show a broad and prominent dip around $|t|=4 \text{ (GeV/c)}^2$. There is no indication of a corresponding dip development in our 50 GeV/c data. Beyond the dip the 200 GeV/c data indicate a $|t|^{-7}$ fall-off (section 4.1.4).

The π^-p differential cross sections between 20 and 200 GeV/c are virtually energy independent below $|t| \approx 2.8 \text{ (GeV/c)}^2$ [2]. In fact, disregarding the considerable difference in the dip region, the energy independence extends to $|t| \approx 5 \text{ (GeV/c)}^2$. The energy independence and the existence of dips indicate that the cross sections are essentially diffractive up to $|t| \approx 5 \text{ (GeV/c)}^2$. The π^+p 50 GeV/c data are slightly above the π^-p 50 GeV/c data in this region, suggesting a small charge dependence of πp cross sections. Moreover, a

comparison with π^+p data at 100 and 200 GeV/c suggest a small energy dependence of π^+p cross sections between 50 and 200 GeV/c [22].

The K^-p 20 GeV/c elastic differential cross section (Table 8) is shown in Fig.10 together with large- $|t|$ ($|t| > 7$ (GeV/c) 2) data at 20 GeV/c from the large-angle phase of this experiment [6]. The diffractive peak falls exponentially for $0.6 < |t| < 2.7$ (GeV/c) 2 , decreasing by roughly four orders of magnitude in this range. A minor change of slope is observed near $|t| = 1$ (GeV/c) 2 , where the slope parameter B changes from 5.4 ± 0.5 to 4.4 ± 0.2 (GeV/c) $^{-2}$. A similar change of slope was observed in the π^-p 20 GeV/c data. However, the π^-p slope is slightly steeper at both sides of the break (6.2 ± 0.5 and 4.8 ± 0.2), crossing K^-p around $|t| = 1.5$ (GeV/c) 2 . A similar result has been obtained at 100 and 200 GeV/c by Baker et al.[22], who report a cross-over around $|t| = 1$ (GeV/c) 2 . Apart from the small difference in slope, the K^-p and π^-p 20 GeV/c cross sections are strikingly similar up to $|t| \approx 2.7$ (GeV/c) 2 , as illustrated by the smoothed π^-p data in Fig.10. Approximate equality has also been reported at 100 and 200 GeV/c for $|t| < 2.5$ (GeV/c) 2 [22]. The K^-p 20 GeV/c data feature a prominent change of slope around $|t| = 3$ (GeV/c) 2 , followed by a less steep fall-off.

The K^+p 50 GeV/c elastic differential cross section (Table 9), presented in Fig.11, shows an exponential fall between $0.7 < |t| < 2.8$ (GeV/c) 2 . The slope parameter B is 4.5 ± 0.2 (GeV/c) $^{-2}$, roughly equal to the π^+p 50 GeV/c slope parameter (4.6 ± 0.2). Like π^+p , the K^+p cross section features a shallow dip around $|t| = 3.8$ (GeV/c) 2 . The smoothed curve in Fig.11 illustrates the strong similarity between the K^+p and π^+p 50 GeV/c cross sections over the entire measured t -range.

In the following sections, some models treating elastic meson-proton scattering are reviewed and confronted with data in the energy range 20 to 200 GeV/c.

4.1.1 Geometrical Scaling

Assuming the real part of the scattering amplitude is zero ($\rho = \text{Re}F/\text{Im}F = 0$ at $t=0$), geometrical scaling (GS) [35-37] implies that the elastic amplitude can be written $\text{Im}F(s,t) = \text{Im}F(s,0)\Phi(\tau)$. $\Phi(\tau)$ is a scaling function which is universal for channels with equal and constant $\sigma_{\text{el}}/\sigma_{\text{tot}}$, and $\tau = -t\sigma_{\text{tot}}$ is the scaling variable. It has been shown that if $\sigma_{\text{tot}} \sim (\ln s)^2$, GS behaviour emerges asymptotically as a consequence of first principles [38].

It follows from the simple ($\rho=0$) GS formalism that differential cross sections of channels with equal and constant $\sigma_{\text{el}}/\sigma_{\text{tot}}$ can be represented by a universal curve when plotting $1/\sigma_{\text{tot}}^2 \cdot d\sigma/dt$ versus $-t\sigma_{\text{tot}}$. Such a plot is shown in Fig.12 for π^-p 20-200 GeV/c, π^+p 50 GeV/c, K^-p 20 GeV/c and K^+p 50 GeV/c ($1 < |t| < 4$ (GeV/c) 2). There is a clear indication that the πp and Kp data fall on respective GS curves for $|t| < 2.8$ (GeV/c) 2 . This reflects the energy independence of the differential cross sections, coupled with little energy dependence of the total cross sections ($\Delta\sigma_{\text{tot}}(\pi p) \sim 2\text{mb}$ [39], $\Delta\sigma_{\text{tot}}(Kp) \sim 3\text{mb}$ [40]). The slight separation between the πp and Kp GS curves is a combined effect of equal $d\sigma/dt$ and different σ_{tot} . Baker et al. have observed a similar separation at ± 100 GeV/c, and conclude that this constitutes a significant deviation from GS behaviour [22]. It can be argued that this conclusion is correct only if the plateau values of $\sigma_{\text{el}}/\sigma_{\text{tot}}$ are equal for πp and Kp . However, world data up to 200 GeV/c [39,40] indicate a small difference in ratios (0.14 vs. 0.125 for $p_{\text{lab}} > 50$ GeV/c), which naturally introduces scaling violations between πp and Kp .

Above $|t| \approx 2.8 \text{ (GeV/c)}^2$, the data deviate from a GS curve (Fig.12), reflecting the considerable energy dependence in the dip region. This deviation from simple GS can be attributed to a non-negligible real part: $\rho_{\pi^-p}(t=0)$ has been measured to be -0.04 ± 0.02 at -30 GeV/c , -0.003 ± 0.013 at -50 GeV/c and $+0.064 \pm 0.011$ at -200 GeV/c [41]. The GS model of Dias de Deus and Kroll [36] includes the real part $\text{Re}F(s,t) = \text{Re}F(s,0) \cdot d/d\tau\{\tau\Phi(\tau)\}$. The dip is due to a zero in the scaling function $\Phi(\tau)$, and hence the cross section in the dip is directly related to the real part contribution given by ρ . Using this relation, Kroll [37] has calculated ρ_{π^-p} from the 200 GeV/c differential cross section, and finds $\rho = 0.04 \pm 0.03$, in reasonable agreement with the experimental data. The existence of πp data at 50 GeV/c will allow a similar test to be made of the GS model at lower energies. In fact, world data on elastic and total $\pi^\pm p$ cross sections [39] indicate that σ_{el}/σ_{tot} has just reached a plateau (≈ 0.14) at 50 GeV/c , thus satisfying the GS condition that σ_{el}/σ_{tot} stay constant with energy (at 20 GeV/c , σ_{el}/σ_{tot} is still decreasing with increasing energy). A priori, the absence of a dip in the π^-p 50 GeV/c cross section seems hard to explain within the GS picture. Given the negligible real part measured at 50 GeV/c (-0.003), one would expect a deeper dip at 50 GeV/c than at 200 GeV/c . This apparent inconsistency may indicate a breakdown of GS below 200 GeV/c .

4.1.2 Generalized Geometrical Scaling

Generalized geometrical scaling (GS), as suggested by Barger, Luthe and Phillips [42], allows GS to be applied between channels with different σ_{el}/σ_{tot} . Of the four rescaling prescriptions given, only the rescaling of the unabsorbed overlap function τ_0 from pp data at $\sqrt{s}=53 \text{ GeV}$ comes close to describe our $\pi^\pm$ data. However, as illustrated in Fig.7, this rescaling produces a narrow dip

around $|t|=4$ (GeV/c)² at 50 GeV/c, in clear disagreement with the structureless π^-p data at this energy. In fact, τ_0 rescaling also fails to reproduce the π^-p 200 GeV/c data above $|t|\approx 1$ (GeV/c)². In particular, the prediction of a narrow dip appears to be a general feature of all rescalings from pp data. The broad dip observed at 200 GeV/c is therefore difficult to describe within this picture.

A rescaling of the eikonal from pp data at $\sqrt{s}=53$ GeV gives good agreement with the K^+p 50 GeV/c data, as illustrated in Fig.13a. However, the same method applied to π^+p 50 GeV/c does not agree nearly so well with data (Fig.13b), giving a dip around $|t|=3.2$ (GeV/c)², instead of the observed value of $|t|\approx 3.8$ (GeV/c)². The fact that none of the four rescaling prescriptions given in ref.[42] can describe both the π^+p and K^+p data clearly casts doubt upon the suggested generalizations of geometrical scaling.

4.1.3 The Chou-Yang Geometrical Model and the Pion Form Factor

In the purely diffractive model of Chou and Yang [27,43], the opacity, which describes the absorption probability, is factorized as $\Omega(b,s)=K(s)\cdot F(b)$. $F(b)$ is taken as the two-dimensional Fourier transform of the electromagnetic form factor product, while $K(s)$ is determined by the total cross section using the optical theorem. Thus, given the form factors of the interacting particles, the differential cross section is a function of σ_{tot} only. However, the large- q^2 dependence of the pion electromagnetic form factor is not well known; available large- q^2 data from electroproduction ($q^2>3$ (GeV/c)² [44]) are scarce and have substantial errors.⁸

⁸ A fit of the few data points to the pole form $(1+q^2/m^2)^{-1}$ yields $m^2=0.462\pm 0.012$ (GeV/c)² [44].

Chan et al. [45] have extrapolated the pion form factor to large q^2 by applying two analytic forms which agree with low- q^2 form factor data [46]: the Vector Meson Dominance (VMD) form $F_\pi(q^2) = (1+q^2/m_\rho^2)^{-1}$, and the Additive Quark Model (AQM) form $F_\pi(q^2) = F_p(q^2)^{2/3}$. In both cases the proton dipole form factor $F_p(q^2) = (1+q^2/0.71)^{-2}$ is assumed. Using the Chou-Yang model, Chan et al. found that the VMD form gives good agreement with low- $|t|$ $\pi^\pm p$ data between 70 and 175 GeV/c. Moreover, VMD was found to produce a shallow dip around $|t|=5$ (GeV/c) 2 for π^+p 175 GeV/c, while the AQM form shifted the dip to $|t|\approx 4$ (GeV/c) 2 . The discovery of the $|t|\approx 4$ (GeV/c) 2 dip in the π^-p 200 GeV/c cross section thus seemed to confirm these predictions.

We have calculated the $\pi^\pm p$ 50 GeV/c differential cross sections using the same analytic forms, and find that the VMD form cannot reproduce our π^-p 50 GeV/c data for $|t|>1$ (GeV/c) 2 . This region requires a much stronger q^2 -dependence of the pion form factor than that given by VMD ($\sim(q^2)^{-1}$). Moreover, contrary to the results of Chan et al., the VMD form yields a structureless π^-p cross section at 200 GeV/c when a more precise parametrization of the form factor product is performed [24]. The AQM form has a stronger q^2 -dependence ($\sim(q^2)^{-4/3}$), which leads to a better agreement with the 50 GeV/c data below $|t|\approx 2$ (GeV/c) 2 . However, as seen from Fig.8, the predicted π^+p 50 GeV/c cross section is structureless and falls off too slowly for $|t|>2$ (GeV/c) 2 . This indicates that even the AQM q^2 -dependence is too weak in this region. In fact, the AQM form also fails to produce a dip at 200 GeV/c when the form factor product is represented more precisely [24].

Assuming the validity of the Chou-Yang model, the pion form factor can be extracted from the π^-p 200 GeV/c data by reversing the Chou-Yang method [47-49]. The result is sensitive to the parametrization of the elastic amplitude.

A pion form factor obtained from a parametrization by Karchin and Orear [47] is in good agreement with low- q^2 ($q^2 < 3 \text{ (GeV/c)}^2$) form factor data, and also coincides with the AQM form in this region. At larger q^2 , however, the fall-off is faster ($\approx (q^2)^{-1.7}$) than for the AQM form. In fact, the predicted form factor is in reasonable agreement with a QCD prediction for the large- q^2 dependence of the pion form factor [23]. The parametrization of Bourely et al. [48], satisfying analyticity, implies the existence of a second dip around $|t| \approx 8 \text{ (GeV/c)}^2$ in the 200 GeV/c differential cross section. The resulting form factor coincides with the AQM form up to $q^2 \approx 3 \text{ (GeV/c)}^2$, where it also agrees with the low- q^2 form factor data. At higher q^2 , however, it differs substantially from the AQM form, exhibiting a considerably stronger q^2 -dependence ($\approx (q^2)^{-2}$) in the medium- q^2 region, as well as an abrupt fall to zero for q^2 between 15 and 20 (GeV/c)^2 . A form factor prediction by Lai et al. [49] coincides with that of Bourely et al. up to $q^2 \approx 6 \text{ (GeV/c)}^2$. However, it is structureless with a fast fall-off ($\approx (q^2)^{-2}$) persisting to large q^2 .

These three form factor predictions coincide up to $|t| \approx 5 \text{ (GeV/c)}^2$. At larger $|t|$, the predictions are sensitive to the parametrization of the 200 GeV/c differential cross section and to the interpretation of its large- $|t|$ behaviour. A common feature, however, is that they fall off much faster than the VMD form, and, for $|t| > 3 \text{ (GeV/c)}^2$, even faster than the AQM form. This result is consistent with the form factor behaviour indicated by our 50 GeV/c data, assuming the validity of the Chou-Yang model.

4.1.4 Lowest Order QCD

Large-momentum-transfer exclusive processes have been analysed in perturbative QCD [23], which assumes the dominance of quark and gluon subprocesses at short distances. For πp elastic scattering, the differential cross section is predicted to behave as $d\sigma/dt \sim s^{-1}t^{-7}$ to lowest order, i.e. $d\sigma/dt \sim s^{-8}(t/s)^{-7}$, which has an s^{-8} dependence at fixed s/t ($\cos\theta$). This power-law fall-off with s at fixed scattering angle is consistent with the predictions of the dimensional counting rule [50] and CIM [51], which have the form $d\sigma/dt \sim s^{-8}F(\theta_{\text{cm}})$.

To see whether the lowest order QCD prediction holds in the large- $|t|$ region of the π^+p data, $\log(d\sigma/dt \cdot s^8)$ versus $\log(-t/s)$ has been plotted in Fig.14 for $|t| > 5$ (GeV/c)² at 20, 50 and 200 GeV/c. According to lowest order QCD, the plot should reveal a straight line with slope $|t|^{-7}$. Above $|t| \approx 5$ (GeV/c)², the 200 GeV/c data are not inconsistent with a $|t|^{-7}$ dependence, excluding the single data point around $|t| = 10$ (GeV/c)². The 50 GeV/c data between $5 < |t| < 8$ (GeV/c)² exhibit a $|t|^{-3}$ dependence. The picture presented by the 20 GeV/c data is less clear. Data between $5 < |t| < 10$ (GeV/c)² indicate a $|t|^{-3}$ dependence. The two $|t|^{-3}$ slopes (Fig.14) can be attributed to a normalization problem; our data do not join smoothly on to the large- $|t|$ data of ref.[6], which are a factor ~ 3 higher. However, a $|t|^{-3}$ dependence does not describe the entire large- $|t|$ region ($5 < |t| < 17$ (GeV/c)²) very well. Neither does $|t|^{-4}$, the effective t -dependence in CIM (Fig.6) for $-t \ll s/2$ [51]. At very large $|t|$ ($10 < |t| < 17$), data seem to fall off much faster; in fact, they are not inconsistent with a $|t|^{-7}$ dependence⁹. Moreover, the fixed

⁹ Other large- $|t|$ π^+p data at 20 and 30 GeV/c [6] are not inconsistent with a $|t|^{-7}$ behaviour, but a better description is obtained with a $|t|^{-5}$

angle energy dependence here is close to s^{-8} when extrapolating the $|t|^{-7}$ slope of the 200 GeV/c data to large $-t/s$ (Fig.14). The following picture then emerges: the 20 GeV/c data and the 200 GeV/c data exhibit an approximate lowest order QCD behaviour above $|t| \approx 10 \text{ (GeV/c)}^2$ and $|t| \approx 5 \text{ (GeV/c)}^2$, respectively, while 50 GeV/c data up to $|t| \approx 8 \text{ (GeV/c)}^2$ have not yet reached a QCD regime. This could be interpreted as a decrease of the QCD t -threshold with increasing energy, a behaviour which would imply a transition of the 50 GeV/c data to a $|t|^{-7}$ dependence around $|t| \approx 8 \text{ (GeV/c)}^2$.

The above results are, of course, sensitive to the statistical errors in the data. Moreover, an alternative interpretation of the large- $|t|$ 200 GeV/c data may alter the picture. If the rise in the cross section around $|t| \approx 10 \text{ (GeV/c)}^2$ is considered significant, the agreement with lowest order QCD is lost, a conclusion reached by Orear [24]. One is then faced with the intriguing question whether a second dip develops at large $|t|$.¹⁰ Assuming a diffractive dip is developing here, possible QCD contributions should first be seen above $|t| \approx 10 \text{ (GeV/c)}^2$. This picture indicates a persistently high QCD t -threshold in πp scattering. A more precise measurement of the large- $|t|$ $\pi^- p$ 200 GeV/c cross section is clearly needed to distinguish between the different pictures.

dependence.

¹⁰ Alternatively, the high cross section around $|t| \approx 10 \text{ (GeV/c)}^2$ could be associated with a smooth fall-off of the order of $|t|^{-4}$, as predicted by CIM for $t \ll s/2$ [51].

4.1.5 The Multi-Gluon Exchange Model

In the multi-gluon exchange model of Donnachie and Landshoff [52,53], small- $|t|$ elastic πp scattering is assumed to be controlled by single Pomeron exchange, with a non-negligible contribution from double Pomeron exchange [52]. The Pomeron, which represents a multi-gluon exchange between a pair of quarks, is described by a combination of Regge theory and the Chou-Yang geometrical model. It is seen from ref.[52] that the Pomeron exchange picture provides an adequate description of small- $|t|$ ($|t| < 0.7 \text{ (GeV/c)}^2$) πp data at 200 GeV/c.

Large- $|t|$ elastic πp scattering is described in terms of gluon exchange between valence quarks [53] (the multiple scattering model). The leading diagram is found to be a 2-gluon exchange between the pion quarks and two nucleon quarks. One of the latter goes far off-shell and scatters the third nucleon quark via a gluon exchange. The diagram leads asymptotically to the energy independent behaviour $d\sigma/dt \sim t^{-7}$, $0 \ll |t| \ll s$, which can be written as $d\sigma/dt \sim s^{-7}(t/s)^{-7}$. Higher order QCD corrections could modify the result, and the inclusion of energy dependence cannot be excluded. The model does not predict at which values of s and t the gluon exchange mechanism starts to dominate; however, upper SPS energies are considered worth investigating.

The predicted $|t|^{-7}$ dependence, the same as for lowest order QCD, has already been compared with data in the preceding section (Fig.14). Thus, the weak t -dependence of the 20 and 50 GeV/c data ($\sim |t|^{-3}$) seems to rule out the gluon exchange diagram as the dominant mechanism at lower energies, while the 200 GeV/c data do not exclude such a mechanism. The faster fall-off indicated by the 20 GeV/c data at very large $|t|$ (Fig.14) hardly signals the onset of the gluon exchange mechanism, since the fixed angle energy dependence between

these data and the extrapolated ($|t|^{-7}$) 200 GeV/c data is stronger ($\sim s^{-8}$) than the predicted s^{-7} dependence. Obviously, a real test of the model requires large- $|t|$ πp data at energies above 200 GeV/c.

4.2 $\bar{p}p$ AND pp ELASTIC SCATTERING

The $\bar{p}p$ 30 GeV/c elastic differential cross section (Table 10), shown in Fig.15, falls exponentially between $0.5 < |t| < 1.4$ (GeV/c)². A change of slope is observed near $|t|=0.9$ (GeV/c)², where the slope parameter B changes from 9.0 ± 0.2 to 6.5 ± 0.2 (GeV/c)⁻². The most prominent feature, however, is a sharp dip around $|t|=1.7$ (GeV/c)², followed by a second maximum and a subsequent power fall-off in $|t|$ ($\sim |t|^{-\alpha}$, $\alpha=6.5 \pm 0.3$, $|t| > 2.5$ (GeV/c)²).

The $\bar{p}p$ 50 GeV/c elastic differential cross section (Table 11), also shown in Fig.15, exhibits an exponential fall-off between $0.7 < |t| < 1.3$ (GeV/c)². There is no evidence for a change of slope in this region; the slope parameter B is found to be 9.7 ± 0.3 (GeV/c)⁻², somewhat higher than at 30 GeV/c. A very pronounced dip is observed around $|t|=1.5$ (GeV/c)², followed by a second maximum and a power fall-off in $|t|$ ($\sim |t|^{-\alpha}$, $\alpha=6.0 \pm 0.3$, $|t| > 2.5$ (GeV/c)²). Our data thus show that the dip moves towards smaller $|t|$ -values ("inward") as the energy increases from 30 to 50 GeV/c.

Fig.16 provides a comparison with lower energy $\bar{p}p$ data at 5 GeV/c [15], 6.2 GeV/c [16] and 10.1 GeV/c [17]. A dip structure, which turns into a shoulder at 10 GeV/c, is seen around $|t|=0.5$ (GeV/c)². It is natural to associate this structure with the change of slope near $|t|=0.9$ (GeV/c)² at 30 GeV/c, which has been totally suppressed at 50 GeV/c. The 5 and

6.2 GeV/c cross sections exhibit a shoulder around $|t| \approx 2 \text{ (GeV/c)}^2$, while the 10 GeV/c data indicate the existence of a shallow dip in this region. The inward dip movement observed when increasing the energy from 30 to 50 GeV/c now naturally associates the prominent dip at these energies with the $|t| \approx 2 \text{ (GeV/c)}^2$ structure seen at 10 GeV/c. One is thus led to conclude that the dip must develop rapidly between 10 and 30 GeV/c, and move towards smaller $|t|$ -values as the energy is increased.

Fermilab $\bar{p}p$ data at 100 and 200 GeV/c [9] indicate that the dip persists to higher energies. The dip position is uncertain due to poor statistics, but the data suggest little dip movement between 50 and 200 GeV/c.

Preliminary data at $\sqrt{s}=546 \text{ GeV}$ from the CERN $S\bar{p}pS$ collider (UA4) are now available up to $|t| \approx 1.6 \text{ (GeV/c)}^2$ [18]. At this energy, the $\bar{p}p$ elastic differential cross section features an abrupt change of slope around $|t| = 0.8 \text{ (GeV/c)}^2$, followed by a shoulder. Although final conclusions must await better statistics at medium- t , it seems clear that the lower energy dip has been practically filled at the collider. Data at intermediate energies are needed to investigate how rapidly the dip is filled. There is actually an indication of a shallow dip or a shoulder in preliminary $\bar{p}p$ data at $\sqrt{s}=52.8 \text{ GeV}$ [54].

The pp 50 GeV/c elastic differential cross section (Table 12) is shown in Fig.17. pp 50 GeV/c data at small- $|t|$ ($|t| < 0.8 \text{ (GeV/c)}^2$) from Akerlof et al.[21] and the $\bar{p}p$ 50 GeV/c data from this experiment are also shown for comparison. Our pp 50 GeV/c data are seen to join smoothly the small- $|t|$ data of Akerlof et al.. Between $0.8 < |t| < 1.4 \text{ (GeV/c)}^2$ the cross section falls exponentially as $\exp\{(8.4 \pm 0.5)t\}$. There is a pronounced change of slope around $|t| = 1.4 \text{ (GeV/c)}^2$, followed by a shoulder and a subsequent power fall-off in $|t|$

($|t|^{-\alpha}$, $\alpha=6.0\pm0.3$, $|t|>2$ (GeV/c)²). A similar structure is reported by Rusack et al. [8] at the same momentum. The shoulder contrasts with the sharp dip in the $\bar{p}p$ differential cross section at the same energy and momentum transfer. Within the experimental errors, the pp and $\bar{p}p$ data nevertheless coincide in the small- $|t|$ region ($|t|<1$ (GeV/c)²), and in the high- $|t|$ region ($|t|>2.5$ (GeV/c)²).

Fig.18 provides a comparison with pp data at lower and higher energies. The pp 24 GeV/c data of Allaby et al. [7] show characteristics similar to those of the 50 GeV/c data, but the change of slope occurs at a somewhat smaller $|t|$ -value ($|t|\approx 1.3$ (GeV/c)²), and the cross section is systematically higher. The higher energy data show that the 50 GeV/c shoulder has developed to a shallow dip around $|t|=1.4$ (GeV/c)² at 100 GeV/c [9], and to a more pronounced dip at the same $|t|$ -value at 200 GeV/c [9,10]. The dip thus develops with increasing energy, and is seen to be very pronounced in pp data at $\sqrt{s}=44.6$ GeV ($p_{lab}\approx 1060$ GeV/c) [11]. In fact, there is a striking similarity between pp elastic differential cross sections at ISR energies and that of $\bar{p}p$ at 50 GeV/c. The $\bar{p}p$ 50 GeV/c data almost coincide [1] with the pp data at $\sqrt{s}=44.6$ GeV. This illustrates the fact that $\bar{p}p$ develops a prominent dip at a much lower energy than pp .

There are several interpretations of the dips and shoulders. Below, some prominent models for elastic NN scattering are reviewed and confronted with pp and $\bar{p}p$ data in the medium- $|t|$ (dip) region. (Section 4.2.5 covers the fixed- t energy dependence of pp and $\bar{p}p$ elastic scattering).

4.2.1 Geometrical Scaling

In the geometrical scaling (GS) model [35-37] (see 4.1.1), the dip is diffractive, being due to a zero in the imaginary part of the amplitude: $\text{Im}F(s,t) = \text{Im}F(s,0)\Phi(\tau)$, $\tau = -t\sigma_{\text{tot}}(s)$. This occurs when the scaling function $\Phi(\tau)$ is zero. $\Phi(\tau)$ is universal in the GS regime, and is determined from pp data at $\sqrt{s}=53$ GeV. The real part $\text{Re}F(s,t) = \text{Re}F(s,0)d/d\tau\{\tau\Phi(\tau)\}$ is directly related to the cross section in the dip, and may fill it up, depending on $\rho = \text{Re}F(s,0)/\text{Im}F(s,0)$ [36].

The dip position scales in $|t|$ according to $|t|_{\text{dip}} \sim 1/\sigma_{\text{tot}}$. Since $\sigma_{\text{tot}}(\bar{p}p)$ decreases when going from 30 to 50 GeV/c, GS predicts a $\bar{p}p$ dip movement towards larger $|t|$, in direct opposition to the observed inward dip movement with increasing energy. It is clear that a principal scaling violation is observed in the 30-50 GeV/c momentum range, effectively establishing a lower limit for a GS regime. The result is not surprising, since 30 and 50 GeV/c are rather low momenta for the application of asymptotic concepts like GS. For instance, scaling violations are bound to occur if the elastic amplitude has appreciable non-diffractive components. Ref.[37] gives a quantitative measure of the GS violation at 50 GeV/c. Using the pp eikonal χ_{pp} at $\sqrt{s}=53$ GeV [36], and expressing the $\bar{p}p$ 50 GeV/c eikonal as $\text{Im}\chi_{\bar{p}p}(b/R_{\bar{p}p}) = \lambda \text{Im}\chi_{pp}(b/R_{pp})$, where $R_{pp}=1$, the parameters λ , $R_{\bar{p}p}$ and ρ are fitted to the $\bar{p}p$ 50 GeV/c differential cross section. A good fit to the data is obtained with $\lambda=0.95$, $R_{\bar{p}p}=1.08$ and $\rho=-0.02$. In contrast, eikonal universality gives $\lambda=R_{\bar{p}p}=1$ in the asymptotic GS regime.

In the GS picture, the difference between $\bar{p}p$ and pp in the dip region can be explained by their different real part contributions at lower energies, as

expressed by ρ . However, the relation between ρ and $d\sigma/dt$ in the dip does not work quantitatively below ISR energies [55].

At ISR energies, GS works well for pp scattering [26]. $\bar{p}p$ is predicted to be almost identical to pp ; however, given the small difference in σ_{tot} and ρ , the $\bar{p}p$ dip is somewhat shallower and at a slightly smaller $|t|$ -value than the pp dip.

GS correctly predicts a shoulder at the $S\bar{p}pS$ collider, assuming $\rho=0.15$ [56]. However, the predicted shoulder is a factor ~ 10 below the preliminary UA4 data. This disagreement provides a severe challenge to the GS model, which is founded on the assumption that the asymptotic regime has already been reached at present collider energies.

4.2.2 Factorizing Eikonal Models

Another class of geometrical models in the impact parameter representation factorizes the eikonal [27,28,57]. In these models, the asymptotic regime is far away from present collider energies.

i) the Chou-Yang model

In the geometrical model of Chou and Yang [27] (see 4.1.3), pp and $\bar{p}p$ elastic differential cross sections can be calculated from the electromagnetic form factor of the proton. The difference between pp and $\bar{p}p$ is explained by their different total cross sections. Several dips are predicted due to interference between scattering amplitude terms. Like in GS, a decreasing total cross section forces the dip towards higher $|t|$ -values, and vice versa.

At lower energies, $\sigma_{\text{tot}}(\bar{p}p)$ decreases with increasing energy, and the Chou-Yang model leads to a $\bar{p}p$ dip movement towards higher $|t|$. Chou and Yang thus associated the $\bar{p}p$ 50 GeV/c dip at $|t| \approx 1.5 (\text{GeV}/c)^2$ with the lower energy dip structure around $|t| \approx 0.5 (\text{GeV}/c)^2$, and predicted a dip near $|t| \approx 1.1 (\text{GeV}/c)^2$ at 30 GeV/c [58]. This dip movement is opposite to what we observe. It shows that a strict interpretation of the geometrical picture does not work at lower energies.

The absence of a dip in low energy pp scattering is attributed to low energy effects, which for $\bar{p}p$ should be less overwhelming due to the larger total cross section [58]. A recent inclusion of a real part [59] (see below) can possibly provide a more precise, however qualitative, interpretation of the low-energy pp shoulder.

At ISR energies, the predicted movement of the pp dip is in qualitative agreement with data, although it is too fast [27]. The $\bar{p}p$ differential cross section is predicted to become similar to that of pp , and to exhibit a pronounced dip around $|t| \approx 1.2 (\text{GeV}/c)^2$ at $\sqrt{s} = 53 \text{ GeV}$ [27]. The dip continues to move inwards with increasing energy, reaching $|t| \approx 0.7 (\text{GeV}/c)^2$ at the $S\bar{p}pS$ collider when using $\sigma_{\text{tot}} = 67 \text{ mb}$. The prediction of a dip is in clear disagreement with the preliminary $S\bar{p}pS$ collider data from UA4. Moreover, the predicted second maximum is a factor ~ 10 above the observed shoulder [27]. It has thus been necessary to modify the geometrical picture by including the real part of the amplitude, which effectively transforms the dip to a shoulder, using $\rho = 0.20$ [59]¹¹.

¹¹ The predicted shoulder is still too high by roughly a factor 3, using $\sigma_{\text{tot}} = 67 \text{ mb}$. However, the recent revision of $\sigma_{\text{tot}}(\sqrt{s} = 546 \text{ GeV})$ to 62 mb [18]

ii) the Bourrely-Soffer-Wu model

Bourrely, Soffer and Wu [28] have proposed modifications to the simple impact parameter picture of Chou and Yang to describe low energy pp data, the slow fall-off of the pp differential cross section beyond the second maximum and the absence of a second dip, and real part effects. A low energy Regge background is added to the opacity. At high energies, the Pomeron term dominates. The s - and b -dependence of the Pomeron term is factorized at the level of the Born term. The energy dependent function is crossing symmetric and incorporates a real part, which is thus "built in". Furthermore, the large- $|t|$ behaviour of the pp cross sections requires a functional correction to the simple relation between $F(b)$ and the proton form factor, with the latter taken to be a dipole form which deviates somewhat from the measured electromagnetic form factor at large $|t|$. Dips are due to zeros in the imaginary part of the amplitude, and may be filled by the real part.

The model, which is in good agreement with pp data over a wide energy range [28], has recently been applied to $\bar{p}p$ scattering [60]. At lower energies (WA7), a unified description of pp and $\bar{p}p$ seems hard to obtain with conventional Regge contributions [61]. It should be noted, though, that the inward dip movement predicted for $\bar{p}p$ is in qualitative agreement with the $\bar{p}p$ data at 30 and 50 GeV/c, although it is too slow [60].

should imply a better agreement.

Due to a vanishing Regge background and the crossing symmetric Pomeron term, pp and $\bar{p}p$ differential cross sections become practically equal at upper ISR energies. A dip is thus predicted around $|t|=1.3 \text{ (GeV/c)}^2$ in the $\bar{p}p$ cross section at $\sqrt{s}=53 \text{ GeV}$. The zero in the imaginary amplitude, and hence the dip structure, moves smoothly towards lower $|t|$ with increasing energy. At the $S\bar{p}pS$ collider, the dip is filled in, and the predicted cross section is in fair agreement with data [60]. In fact, a unified description of pp and $\bar{p}p$ data ($d\sigma/dt, \sigma_{\text{tot}}, \rho$) is obtained in the ISR- $S\bar{p}pS$ collider energy range. However, the predicted $\bar{p}p$ dip at ISR energies has yet to be observed.

4.2.3 The Multi-Gluon Exchange Model

In a totally different and dynamical picture, Donnachie and Landshoff describes high energy elastic NN scattering in terms of various exchange processes [29,53] (the overall picture of elastic NN scattering is analogous to that proposed for elastic πp scattering, see section 4.1.5). At large $|t|$, triple-gluon exchange (3g) dominates (the multiple scattering model [53]). At small $|t|$, the dominant contribution is a single Pomeron exchange (1P) between the protons. 1P represents a multi-gluon exchange between a pair of quarks, and is described by a combination of Regge theory and the Chou-Yang model. A dip is produced by cancellation of terms. To cancel $\text{Im}(1P)$ in the dip region, a double Pomeron exchange (2P) is introduced. In pp scattering, $\text{Re}(1P)$ and $\text{Re}(2P)$ are cancelled by 3g, which is real to lowest order in QCD. However, since 3g is $C=-1$, it does not cancel the real part in $\bar{p}p$ scattering. Thus, at ISR energies and beyond, a dip is predicted for pp , while $\bar{p}p$ should exhibit only a shoulder. To reproduce the dip observed in the $\bar{p}p$ 50 GeV/c cross section, an additional Regge-Pomeron exchange (RP) is needed at low energies to cancel the real part. Consequently, the dip in $\bar{p}p$ scattering originates from a

different mechanism than the higher energy pp dip, and should disappear rapidly with energy. In fact, the similarity between the $\bar{p}p$ 50 GeV/c cross section and that of pp at ISR energies is regarded as accidental.

The model does not describe low energy pp scattering. However, an interpretation of the pp shoulder similar to that of the $\bar{p}p$ dip (a low energy phenomenon originating from Regge-Pomeron exchange) seems natural within this picture.

The model is in qualitative agreement with the $\bar{p}p$ 50 GeV/c data [29]. However, the t -dependence of 2P and RP is not well known, adding uncertainty to the prediction. At ISR energies, good agreement is obtained with pp data. Moreover, there is an indication of the predicted $\bar{p}p$ shoulder (or a shallow dip) in the preliminary $\bar{p}p$ data at $\sqrt{s}=52.8$ GeV [54]. At the S $\bar{p}p$ S collider, the predicted shoulder is a factor of ~ 10 below the preliminary UA4 data, and it is located at a somewhat higher $|t|$ -value.

Two points should be noted. Firstly, the difference between pp and $\bar{p}p$ in the dip region, caused by the $3g$ term, cannot persist asymptotically without violating the Cornille-Martin theorem [62], which states that pp and $\bar{p}p$ become equal at asymptotic energies. Secondly, the Donnachie-Landshoff model is based on the assumption that elastic scattering probes different processes in different regimes of t and s , which require both QCD and Regge exchange descriptions. It is clear, however, that the fundamental problem how to bring together Regge theory and QCD remains unsolved, as is evident from the phenomenological description of the Pomeron.

4.2.4 The Nucleon Core Model

Another dynamical picture is presented in the nucleon core model of Islam et al. [30,63,64]. High energy elastic NN scattering is described in terms of two processes. Diffraction, described by a direct-channel Regge pole, dominates at small $|t|$. At large $|t|$ hard scattering takes over. This originates from the scattering of nucleon valence-quark cores via the exchange of a vector meson ω , while outer hadronic clouds of sea quarks interact independently by a Regge-pole exchange. A dip is produced by destructive interference between the diffractive and hard scattering amplitudes. At large momentum transfers, the hard scattering should lead smoothly to the quark interchange mechanism (CIM) [63]. The model contains a set of diffractive and hard scattering parameters which have been determined [30] from fits to pp data at 50 GeV/c and $\sqrt{s}=52.8$ GeV, and to the preliminary $S\bar{p}pS$ collider data. The hard scattering parameters are the same for pp and $\bar{p}p$, while the energy dependent diffraction parameters are different at finite energies. This difference leads to the prediction of a persistent difference in pp and $\bar{p}p$ cross sections at all presently accessible energies. In fact, asymptopia, where pp and $\bar{p}p$ become equal, is extremely remote and practically inaccessible (the energy at which the pp and $\bar{p}p$ diffraction parameters of ref. [30] become comparable is of the order of $\sqrt{s}>10^{36}$ GeV).

The model describes dips and shoulders as manifestations of the same destructive interference between two processes. At low energies, the interference term is small for pp while near its maximum for $\bar{p}p$, producing a shoulder and a prominent dip, respectively. The model is in good agreement with pp data away from the forward direction at energies ranging from 30 GeV/c to $\sqrt{s}=62.1$ GeV (2056 GeV/c) [30]. The model fit to the pp 50 GeV/c data is

shown in Fig.17. While the dip in pp cross sections corresponds to the first destructive interference, the $\bar{p}p$ dip corresponds to the second destructive interference, and should therefore be associated with the 10 GeV/c structure around $|t|=2$ (GeV/c)². The model thus correctly leads to the observed inward dip movement with increasing energy [64]. Fig.15 shows the fits to the $\bar{p}p$ 30 and 50 GeV/c cross sections [30]. A qualitative agreement is obtained.

In contrast to the Donnachie-Landshoff prediction, the $\bar{p}p$ dip persists to ISR energies, and is predicted to be located around $|t|=1.1$ (GeV/c)² at $\sqrt{s}=53$ GeV [30]. Moving further inwards while slowly filling up, the $\bar{p}p$ and pp dips are transformed to shoulders at the $S\bar{p}pS$ collider energy. Good agreement is obtained with the preliminary UA4 data away from the forward direction [30]. It should be noted that in this model, pp and $\bar{p}p$ dips originate from the same mechanism. Moreover, the sharp dips at 30 and 50 GeV/c are directly related to the shoulder at the $S\bar{p}pS$ collider, making the WA7 energies a "window" to the high energy regime.

4.2.5 Energy Dependence

The fixed- t energy dependence of pp differential cross sections is shown in Fig.19 [4] for $|t|$ -values between 2 and 14 (GeV/c)² and momenta ranging from 9 to 1486 GeV/c ($\sqrt{s}=52.8$ GeV). At any fixed $|t|$ -value, $d\sigma/dt$ falls with increasing energy, but the rate of fall decreases rapidly with energy, eventually flattening out. An asymptotic behaviour thus appears to set in above a certain energy. This threshold energy seems to increase with $|t|$. For $|t|<4$ (GeV/c)² an asymptotic regime is apparently reached above ~ 200 GeV/c. For higher $|t|$ -values, asymptopia is not yet reached at this energy. Our 50 GeV/c data are seen to lie in the energy region where the slopes start to

change, while it is still possible to parametrize the differential cross section at fixed $|t|$ as

$$d\sigma/dt \sim p_{\text{lab}}^{-\alpha}, \quad p_{\text{lab}} < 50 \text{ GeV/c}, \quad |t| < 4 \text{ (GeV/c)}^2.$$

$\alpha(t)$ is found to increase roughly linearly with $|t|$ as $\alpha(t) \approx 0.6|t| + 0.7$. At higher $|t|$ -values the same parametrization is found to hold for smaller momenta.

The result can be compared with the fixed- t energy dependence of $\bar{p}p$ differential cross sections, shown in Fig.20 [5] for momenta between 3.6 and 50 GeV/c and $|t|$ -values at 2.0 and 4.0 (GeV/c)². There is no indication of an asymptotic energy development in this low-energy range. The data fit nicely the power-law form $d\sigma/dt \sim p_{\text{lab}}^{-\alpha}$, where $\alpha \approx 2.5$ for $|t| = 2 \text{ (GeV/c)}^2$ and $\alpha \approx 1.6$ for $|t| = 4 \text{ (GeV/c)}^2$. However, $\bar{p}p$ data at 100 and 200 GeV/c show little energy dependence at fixed $|t|$ [9].

The apparent onset of an energy independent behaviour supports predictions by the multi-gluon exchange model of Donnachie and Landshoff [53] (section 4.2.3), in which the dominant mechanism at large t and s is triple gluon exchange between quark pairs. The diagram leads asymptotically to the energy independent behaviour $d\sigma/dt \sim t^{-8}$, $0 \ll |t| \ll s$, i.e. $d\sigma/dt \sim s^{-8}(t/s)^{-8}$. The prediction is in approximate agreement with large- $|t|$ ($|t| > 4 \text{ (GeV/c)}^2$) pp data in the upper-Fermilab to ISR energy range; data at 200 GeV/c [65] and $\sqrt{s} = 52.8 \text{ GeV}$ [11] exhibit approximately the behaviour $d\sigma/dt \sim s^{-0.5} t^{-8.2}$ for $|t| > 4 \text{ (GeV/c)}^2$. The stronger energy dependence at PS energies is consistent with s^{-10} at fixed t/s ($\cos\theta$) for $|t| > 2.5 \text{ (GeV/c)}^2$ [66]. This fixed angle energy dependence is in agreement with the dimensional counting rule [50] and CIM [51], which predict $d\sigma/dt \sim s^{-10} F(\theta_{\text{cm}})$, and with a lowest order QCD prediction [23] which has the form $d\sigma/dt \sim s^{-2} t^{-8} \sim s^{-10} (t/s)^{-8}$.

5. CONCLUSIONS

Elastic differential cross sections have been presented for π^-p 20 GeV/c, π^+p 50 GeV/c, K^-p 20 GeV/c and K^+p 50 GeV/c scattering in the t -range $0.6 < |t| < 8$ (GeV/c)², and for $\bar{p}p$ 30 GeV/c and $\bar{p}p/pp$ 50 GeV/c scattering in the t -range $0.5 < |t| < 5.8$ (GeV/c)².

i) πp and Kp :

The dip around $|t|=2.8$ (GeV/c)² observed in lower energy π^-p scattering [19] is gradually filled in with increasing energy; at 50 GeV/c only a change of slope remains. The π^+p 50 GeV/c cross section, however, shows a small dip around $|t|=3.8$ (GeV/c)². The π^-p 50 GeV/c data do not indicate any development towards the broad dip around $|t|=4$ (GeV/c)² seen at 200 GeV/c [22]. π^-p elastic differential cross sections between 20 and 200 GeV/c are virtually energy independent for $|t| < 2.8$ (GeV/c)², while a small energy dependence cannot be ruled out in π^+p scattering [22]. There is strong similarity between πp and Kp differential cross sections over the entire measured t -range, although forward slopes are slightly steeper in πp than in Kp . This approximate equality corroborates results obtained at 100 and 200 GeV/c [22].

πp and Kp exhibit approximate geometrical scaling behaviour [35] below the dip region ($|t| < 2.8$ (GeV/c)²). However, scaling violation in the dip region indicates a breakdown of geometrical scaling below 200 GeV/c, even when real part effects are taken into account.

A suggested generalization of geometrical scaling [42], involving rescaling from pp data, cannot describe our πp data.

A stringent test of the Chou-Yang geometrical model [27,43] must await data on the large- q^2 behaviour of the pion form factor. To describe our πp 50 GeV/c

data within this model, however, a pion form factor with a stronger q^2 -dependence than given by the Additive Quark Model [45] is required. This result is qualitatively consistent with three form factor predictions obtained from a reversed Chou-Yang analysis of the π^-p 200 GeV/c data [47-49].

There are some indications that the π^-p 20-200 GeV/c large- $|t|$ data are consistent with a lowest order QCD prediction [23] above some energy dependent t -values, while data seem to rule out the gluon-exchange diagram of Donnachie and Landshoff [53] as the dominant process below 200 GeV/c. However, more large- $|t|$ data at lower and upper SPS/Fermilab energies are clearly needed to determine the s - and t -dependence of large- $|t|$ πp (and Kp) scattering.

ii) $\bar{p}p$ and pp :

The $\bar{p}p$ elastic differential cross sections at 30 and 50 GeV/c show sharp dips around $|t|=1.7$ (GeV/c) 2 and $|t|=1.5$ (GeV/c) 2 , respectively. Our data thus show that the dip moves towards smaller $|t|$ -values as the energy increases from 30 to 50 GeV/c. It is therefore natural to associate this dip with a shallow dip structure around $|t|=2$ (GeV/c) 2 seen at 10 GeV/c [17].

Recent data at higher energies indicate that the $|t|\approx 1.5$ (GeV/c) 2 dip does not move significantly between 50 and 200 GeV/c [9], while the dip is transformed into a shoulder around $|t|=0.8$ (GeV/c) 2 at the S $\bar{p}p$ S collider energy $\sqrt{s}=546$ GeV [18].

Contrasting with the prominent dip in the $\bar{p}p$ 50 GeV/c differential cross section, pp 50 GeV/c shows only a marked change of slope around $|t|=1.4$ (GeV/c) 2 , followed by a shoulder and a subsequent power fall-off in $|t|$.

Neither the geometrical scaling model nor the Chou-Yang geometrical model can describe the observed $\bar{p}p$ dip movement between 30 and 50 GeV/c, which is opposite to the model predictions [35,58]. This effectively rules out the validity of these models at lower energies.

The modified geometrical model of Bourrely-Soffer-Wu, which includes low energy Regge background, does not provide a unified description of pp and $\bar{p}p$ elastic scattering at 30 and 50 GeV/c [60,61].

The multi-gluon exchange model of Donnachie and Landshoff is in qualitative agreement with the $\bar{p}p$ 50 GeV/c data [29]. The model does not treat low energy pp scattering, however.

In a different dynamical picture, the nucleon core model of Islam et al. provides a unified description of pp and $\bar{p}p$ (non-forward) elastic scattering from 30 GeV/c and upwards. The model describes the pp 50 GeV/c data away from the forward direction, and is in qualitative agreement with the $\bar{p}p$ data at 30 and 50 GeV/c [30].

The lower energy data presented here can, of course, only test the low-energy validity of theoretical models. A more general validity test requires pp and $\bar{p}p$ data at intermediate and high energies. Both the geometrical models and the dynamical exchange-type models discussed here work well for pp scattering at ISR energies [26-30] (the Chou-Yang model, however, is only in qualitative agreement). However, the models can be discriminated by their different predictions for the $\bar{p}p$ differential cross section at ISR energies: a dip (the geometrical models [27,36,60] and the nucleon core model [30]) versus a shoulder (the multi-gluon exchange model [29]). Preliminary $\bar{p}p$ data at $\sqrt{s}=52.8$ GeV indicate a shallow dip or a shoulder [54]. At the S $\bar{p}p$ S collider energy $\sqrt{s}=546$ GeV, the shoulder in the differential cross section is difficult to describe within the geometrical scaling model and the Chou-Yang model [56,59]. However, the modified geometrical model of Bourrely et al. provides a good

description of this region [60]. Good agreement is also obtained by the nucleon core model [30]. The multi-gluon exchange model, on the other hand, only works qualitatively in the shoulder region [29]. A more stringent test of models at high energies requires pp data at a comparable energy.

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Table 1: MWPC characteristics in Period-II

CH	planes	orientations	wire-spacing (mm)	R/O channels total
0	4	V,Y,U,X	2,2,2,1	704
1	5	X,U,Y,V,X	1,2,2,2,1	2496
2	3	X,V,U	1,2,2	1984
3	6	X,U,X,X,V,Y	2,2,2,2,2,2	3808
4	4	U,Y,V,X	4,2,4,2	2848
5	4	X,U,Y,V	4,4,4,4	2144
7	3	Y,X,V	2,2,2	1216
8	3	Y,X,U	2,2,2	1600
9	3	Y,X,V	2,2,2	1504

Table 2: Cerenkov characteristics in Period-II

		C1			C2		
		π	K	p	π	K	p
-30 GeV/c	threshold (GeV/c)	9.2	32.5	61.8	4.9	17.3	33.0
	gas filling	N ₂ /He			CO ₂		
+50 GeV/c	threshold (GeV/c)	7.8	27.5	52.3	7.8	27.5	52.3
	gas filling	N ₂ /He			N ₂ /He		

Table 3: Beam Cerenkov (CP1) characteristics

	π	K	p
Threshold (GeV/c)	12.8	45.4	85.6
Photoelectron yield 20 GeV/c	7.2	0	0
Photoelectron yield 50 GeV/c	11.5	2.2	0

Table 4: Cerenkov characteristics in Period-I

		C1			C2		
		π	K	p	π	K	p
-20 GeV/c	threshold (GeV/c)	6.7	23.5	44.7	3.8	13.3	25.3
	gas filling	N ₂ /He			CO ₂ /Freon		
-50 GeV/c	threshold (GeV/c)	7.8	27.5	52.3	7.8	27.5	52.3
	gas filling	N ₂ /He			N ₂ /He		
+50 GeV/c	threshold (GeV/c)	7.8	27.5	52.3	7.8	27.5	52.3
	gas filling	N ₂ /He			N ₂ /He		

Table 5: $-20 \text{ GeV}/c \quad \pi^- p \rightarrow \pi^- p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.6 - 0.7	29270	$4.2 \pm 3.1 \times 10^{-28}$
0.7 - 0.8	28578	$1.01 \pm 0.24 \times 10^{-28}$
0.8 - 0.9	20815	$4.82 \pm 0.53 \times 10^{-29}$
0.9 - 1.0	14828	$2.96 \pm 0.35 \times 10^{-29}$
1.0 - 1.1	10294	$1.52 \pm 0.15 \times 10^{-29}$
1.1 - 1.2	7211	$1.15 \pm 0.12 \times 10^{-29}$
1.2 - 1.3	5529	$6.61 \pm 0.58 \times 10^{-30}$
1.3 - 1.4	4147	$4.71 \pm 0.42 \times 10^{-30}$
1.4 - 1.5	3080	$2.92 \pm 0.23 \times 10^{-30}$
1.5 - 1.7	3570	$1.25 \pm 0.57 \times 10^{-30}$
1.7 - 1.9	1643	$5.47 \pm 0.27 \times 10^{-31}$
1.9 - 2.1	642	$2.09 \pm 0.12 \times 10^{-31}$
2.1 - 2.3	220	$7.2 \pm 0.6 \times 10^{-32}$
2.3 - 2.5	64	$2.0 \pm 0.3 \times 10^{-32}$
2.5 - 2.7	22	$6.6 \pm 1.6 \times 10^{-33}$
2.7 - 2.9	14	$4.3 \pm 1.5 \times 10^{-33}$
2.9 - 3.1	16	$4.9 \pm 1.3 \times 10^{-33}$
3.1 - 3.5	32	$4.7 \pm 0.9 \times 10^{-33}$
3.5 - 4.0	15	$1.7 \pm 0.5 \times 10^{-33}$
4.0 - 4.5	11	$1.2 \pm 0.4 \times 10^{-33}$
4.5 - 5.5	4.5	$2.3 \pm 1.2 \times 10^{-34}$
5.5 - 6.5	2.5	$1.5 \pm 1.2 \times 10^{-34}$

Table 6: $-50 \text{ GeV}/c \quad \pi^- p \rightarrow \pi^- p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.70- 0.75	16384	$1.27 \pm 0.11 \times 10^{-28}$
0.75- 0.80	17873	$1.06 \pm 0.09 \times 10^{-28}$
0.80- 0.85	18041	$7.04 \pm 0.50 \times 10^{-29}$
0.85- 0.90	17202	$6.25 \pm 0.46 \times 10^{-29}$
0.90- 0.95	15485	$4.43 \pm 0.29 \times 10^{-29}$
0.95- 1.00	13605	$3.47 \pm 0.21 \times 10^{-29}$
1.00- 1.05	11695	$2.52 \pm 0.15 \times 10^{-29}$
1.05- 1.10	9582	$2.05 \pm 0.12 \times 10^{-29}$
1.10- 1.15	8019	$1.48 \pm 0.08 \times 10^{-29}$
1.15- 1.20	6606	$1.16 \pm 0.06 \times 10^{-29}$
1.20- 1.25	5373	$8.29 \pm 0.42 \times 10^{-30}$
1.25- 1.30	4493	$6.81 \pm 0.34 \times 10^{-30}$
1.30- 1.35	3654	$5.61 \pm 0.29 \times 10^{-30}$
1.35- 1.40	3085	$4.06 \pm 0.20 \times 10^{-30}$
1.40- 1.45	2698	$3.29 \pm 0.16 \times 10^{-30}$
1.45- 1.50	2581	$3.11 \pm 0.16 \times 10^{-30}$
1.50- 1.55	2324	$1.61 \pm 0.08 \times 10^{-30}$
1.55- 1.60	2246	$1.40 \pm 0.07 \times 10^{-30}$
1.60- 1.65	2056	$1.06 \pm 0.05 \times 10^{-30}$
1.65- 1.70	1868	$9.38 \pm 0.44 \times 10^{-31}$
1.70- 1.75	1639	$7.33 \pm 0.34 \times 10^{-31}$
1.75- 1.80	1369	$5.53 \pm 0.26 \times 10^{-31}$
1.80- 1.85	1137	$4.31 \pm 0.21 \times 10^{-31}$
1.85- 1.90	985	$3.57 \pm 0.18 \times 10^{-31}$
1.90- 1.95	749	$2.65 \pm 0.14 \times 10^{-31}$

1.95- 2.00	661	$2.25 \pm 0.13 \times 10^{-31}$
2.0 - 2.1	999	$1.62 \pm 0.09 \times 10^{-31}$
2.1 - 2.2	573	$9.51 \pm 0.65 \times 10^{-32}$
2.2 - 2.3	391	$6.27 \pm 0.47 \times 10^{-32}$
2.3 - 2.4	257	$4.40 \pm 0.37 \times 10^{-32}$
2.4 - 2.6	249	$1.94 \pm 0.20 \times 10^{-32}$
2.6 - 2.8	97	$7.35 \pm 1.06 \times 10^{-33}$
2.8 - 3.0	42	$3.60 \pm 0.65 \times 10^{-33}$
3.0 - 3.2	21	$1.67 \pm 0.45 \times 10^{-33}$
3.2 - 3.4	18	$1.44 \pm 0.42 \times 10^{-33}$
3.4 - 3.6	11	$9.1 \pm 3.5 \times 10^{-34}$
3.6 - 3.8	9	$6.5 \pm 2.8 \times 10^{-34}$
3.8 - 4.0	6.4	$4.4 \pm 2.4 \times 10^{-34}$
4.0 - 4.5	18	$4.9 \pm 1.4 \times 10^{-34}$
4.5 - 5.0	10	$2.9 \pm 1.0 \times 10^{-34}$
5.0 - 5.5	10	$2.5 \pm 0.9 \times 10^{-34}$
5.5 - 6.0	7.9	$2.0 \pm 0.8 \times 10^{-34}$
6.0 - 6.5	6.4	$1.5 \pm 0.6 \times 10^{-34}$
6.5 - 7.0	5.6	$1.5 \pm 0.6 \times 10^{-34}$
7.0 - 7.5	3.7	$1.0 \pm 0.6 \times 10^{-34}$
7.5 - 8.0	2.8	$8.2 \pm 5.0 \times 10^{-35}$

Table 7: $\sqrt{s}=50$ GeV/c $\pi^+p \rightarrow \pi^+p$

$ t $ [(GeV/c) ²]	events	$d\sigma/dt$ [cm ² /(GeV/c) ²]
0.7 - 0.8	-	$8.54 \pm 0.87 \times 10^{-29}$
0.8 - 0.9	-	$6.25 \pm 0.77 \times 10^{-29}$
0.9 - 1.0	-	$3.87 \pm 0.55 \times 10^{-29}$
1.0 - 1.1	-	$2.38 \pm 0.37 \times 10^{-29}$
1.1 - 1.2	-	$1.49 \pm 0.24 \times 10^{-29}$
1.2 - 1.3	-	$9.39 \pm 1.58 \times 10^{-30}$
1.3 - 1.4	-	$5.85 \pm 1.01 \times 10^{-30}$
1.4 - 1.5	-	$3.64 \pm 0.64 \times 10^{-30}$
1.5 - 1.6	-	$2.57 \pm 0.45 \times 10^{-30}$
1.6 - 1.7	-	$1.46 \pm 0.21 \times 10^{-30}$
1.7 - 1.8	-	$9.94 \pm 1.62 \times 10^{-31}$
1.8 - 1.9	-	$6.15 \pm 1.09 \times 10^{-31}$
1.9 - 2.0	-	$4.09 \pm 0.73 \times 10^{-31}$
2.0 - 2.2	-	$2.16 \pm 0.39 \times 10^{-31}$
2.2 - 2.4	-	$1.08 \pm 0.19 \times 10^{-31}$
2.4 - 2.6	-	$4.12 \pm 0.82 \times 10^{-32}$
2.6 - 2.8	-	$1.40 \pm 0.30 \times 10^{-32}$
2.8 - 3.0	-	$7.44 \pm 1.83 \times 10^{-33}$
3.0 - 3.2	-	$4.25 \pm 1.23 \times 10^{-33}$
3.2 - 3.6	-	$2.16 \pm 0.69 \times 10^{-33}$
3.6 - 3.8	-	$3.3 \pm 3.5 \times 10^{-34}$ - 3.3
3.8 - 4.0	-	$3.5 \pm 3.8 \times 10^{-34}$ - 3.5
4.0 - 4.5	-	$9.0 \pm 3.5 \times 10^{-34}$

4.5 - 5.0	-	$6.84 \pm 2.80 \times 10^{-34}$
5.0 - 5.5	-	$5.32 \pm 2.27 \times 10^{-34}$
5.5 - 6.0	-	$4.86 \pm 2.06 \times 10^{-34}$
6.0 - 7.0	-	$1.92 \pm 0.91 \times 10^{-34}$
7.0 - 8.0	-	$7.4 \pm 5.7 \times 10^{-35}$

Table 8: $-20 \text{ GeV}/c \quad K^-p \rightarrow K^-p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.6 - 0.7	1684	$2.9 \pm 2.1 \times 10^{-28}$
0.7 - 0.8	1297	$6.34 \pm 1.31 \times 10^{-29}$
0.8 - 0.9	1009	$3.55 \pm 0.26 \times 10^{-29}$
0.9 - 1.0	680	$2.20 \pm 0.16 \times 10^{-29}$
1.0 - 1.1	493	$1.49 \pm 0.11 \times 10^{-29}$
1.1 - 1.2	336	$9.70 \pm 0.78 \times 10^{-30}$
1.2 - 1.3	224	$6.37 \pm 0.55 \times 10^{-30}$
1.3 - 1.4	149	$4.0 \pm 0.4 \times 10^{-30}$
1.4 - 1.5	92	$2.4 \pm 0.3 \times 10^{-30}$
1.5 - 1.7	147	$1.7 \pm 0.2 \times 10^{-30}$
1.7 - 1.9	63	$6.9 \pm 0.9 \times 10^{-31}$
1.9 - 2.1	23	$2.5 \pm 0.6 \times 10^{-31}$
2.1 - 2.3	9.4	$1.0 \pm 0.3 \times 10^{-31}$
2.3 - 2.5	1.8	$1.9 \pm 1.6 \times 10^{-32}$
2.5 - 2.7	1.0	$1.0 \pm 1.0 \times 10^{-32}$
4.0 - 4.5	1.0	$3.7 \pm 3.7 \times 10^{-33}$

Table 9: $+50 \text{ GeV}/c \quad K^+p \rightarrow K^+p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.7 - 0.8	-	$1.01 \pm 0.11 \times 10^{-28}$
0.8 - 0.9	-	$6.75 \pm 0.83 \times 10^{-29}$
0.9 - 1.0	-	$3.70 \pm 0.52 \times 10^{-29}$
1.0 - 1.1	-	$2.57 \pm 0.39 \times 10^{-29}$
1.1 - 1.2	-	$1.63 \pm 0.26 \times 10^{-29}$
1.2 - 1.3	-	$1.03 \pm 0.17 \times 10^{-29}$
1.3 - 1.4	-	$6.05 \pm 0.10 \times 10^{-30}$
1.4 - 1.5	-	$3.92 \pm 0.67 \times 10^{-30}$
1.5 - 1.6	-	$2.75 \pm 0.47 \times 10^{-30}$
1.6 - 1.7	-	$1.52 \pm 0.27 \times 10^{-30}$
1.7 - 1.8	-	$1.22 \pm 0.22 \times 10^{-30}$
1.8 - 1.9	-	$7.68 \pm 1.49 \times 10^{-31}$
1.9 - 2.0	-	$4.85 \pm 0.96 \times 10^{-31}$
2.0 - 2.2	-	$2.98 \pm 0.57 \times 10^{-31}$
2.2 - 2.4	-	$1.22 \pm 0.27 \times 10^{-31}$
2.4 - 2.6	-	$5.19 \pm 1.41 \times 10^{-32}$
2.6 - 2.8	-	$2.19 \pm 0.85 \times 10^{-32}$
2.8 - 3.2	-	$1.12 \pm 0.53 \times 10^{-32}$
3.2 - 3.6	-	$3.1 \pm 2.0 \times 10^{-33}$
3.6 - 4.0	-	$2.4 \pm 6.0 \times 10^{-34}$
		- 2.4
4.0 - 5.0	-	$7.3 \pm 5.7 \times 10^{-34}$
5.0 - 6.0	-	$3.9 \pm 3.9 \times 10^{-34}$
6.0 - 8.0	-	$2.6 \pm 2.2 \times 10^{-34}$

Table 10: $-30 \text{ GeV}/c \quad \bar{p}p \rightarrow \bar{p}p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.50- 0.55	2315	$2.60 \pm 0.12 \times 10^{-28}$
0.55- 0.60	2036	$1.58 \pm 0.07 \times 10^{-28}$
0.60- 0.65	1688	$1.08 \pm 0.05 \times 10^{-28}$
0.65- 0.70	1266	$7.15 \pm 0.34 \times 10^{-29}$
0.70- 0.75	934	$4.43 \pm 0.22 \times 10^{-29}$
0.75- 0.80	722	$2.83 \pm 0.15 \times 10^{-29}$
0.80- 0.85	559	$1.68 \pm 0.10 \times 10^{-29}$
0.85- 0.90	441	$1.17 \pm 0.07 \times 10^{-29}$
0.90- 0.95	409	$8.68 \pm 0.54 \times 10^{-30}$
0.95- 1.00	312	$6.12 \pm 0.43 \times 10^{-30}$
1.0 - 1.1	473	$4.14 \pm 0.24 \times 10^{-30}$
1.1 - 1.2	258	$2.07 \pm 0.15 \times 10^{-30}$
1.2 - 1.3	120	$9.97 \pm 1.03 \times 10^{-31}$
1.3 - 1.4	60	$4.57 \pm 0.69 \times 10^{-31}$
1.4 - 1.5	20	$1.53 \pm 0.41 \times 10^{-31}$
1.5 - 1.6	5.8	$3.9 \pm 2.3 \times 10^{-32}$
1.6 - 1.7	3.2	$1.8 \pm 1.6 \times 10^{-32}$
1.7 - 1.8	3.9	$1.9 \pm 1.4 \times 10^{-32}$
1.8 - 1.9	13	$6.17 \pm 2.03 \times 10^{-32}$
1.9 - 2.0	19	$9.43 \pm 2.74 \times 10^{-32}$
2.0 - 2.2	45	$1.03 \pm 0.19 \times 10^{-31}$
2.2 - 2.4	44	$9.52 \pm 1.78 \times 10^{-32}$
2.4 - 2.6	40	$8.56 \pm 1.66 \times 10^{-32}$
2.6 - 2.8	29	$5.82 \pm 1.27 \times 10^{-32}$
2.8 - 3.0	15	$3.01 \pm 1.02 \times 10^{-32}$

3.0 - 3.4	22	$2.27 \pm 0.56 \times 10^{-32}$
3.4 - 3.8	7.0	$6.78 \pm 2.87 \times 10^{-33}$
3.8 - 4.2	4.3	$3.7 \pm 2.0 \times 10^{-33}$
4.2 - 5.0	1.2	$6.1 \pm 7.3 \times 10^{-34}$ $- 6.1$
5.0 - 5.8	3.4	$1.6 \pm 1.0 \times 10^{-33}$

Table 11: $-50 \text{ GeV}/c \quad \bar{p}p \rightarrow \bar{p}p$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
0.70- 0.75	636	$4.57 \pm 0.42 \times 10^{-29}$
0.75- 0.80	489	$2.93 \pm 0.27 \times 10^{-29}$
0.80- 0.85	401	$1.68 \pm 0.14 \times 10^{-29}$
0.85- 0.90	296	$1.28 \pm 0.11 \times 10^{-29}$
0.90- 0.95	217	$7.73 \pm 0.72 \times 10^{-30}$
0.95- 1.00	151	$4.97 \pm 0.51 \times 10^{-30}$
1.0 - 1.1	190	$2.13 \pm 0.20 \times 10^{-30}$
1.1 - 1.2	97	$1.01 \pm 0.12 \times 10^{-30}$
1.2 - 1.3	28	$2.81 \pm 0.62 \times 10^{-31}$
1.3 - 1.4	2.4	$2.1 \pm 1.7 \times 10^{-32}$
1.4 - 1.5	1.0	$0.8 \pm 1.1 \times 10^{-32}$ $- 0.8$
1.5 - 1.6	1.7	$1.2 \pm 1.2 \times 10^{-32}$
1.6 - 1.7	2.9	$1.8 \pm 1.3 \times 10^{-32}$
1.7 - 1.8	7.2	$4.42 \pm 1.90 \times 10^{-32}$
1.8 - 1.9	9.5	$4.86 \pm 1.63 \times 10^{-32}$
1.9 - 2.0	11	$5.66 \pm 2.14 \times 10^{-32}$

2.0 - 2.2	17	$4.42 \pm 1.11 \times 10^{-32}$
2.2 - 2.4	20	$5.10 \pm 1.23 \times 10^{-32}$
2.4 - 2.6	18	$4.17 \pm 1.09 \times 10^{-32}$
2.6 - 2.8	14	$3.16 \pm 0.95 \times 10^{-32}$
2.8 - 3.0	5.3	$1.45 \pm 0.65 \times 10^{-32}$
3.0 - 3.5	11	$1.17 \pm 0.37 \times 10^{-32}$
3.5 - 4.0	5.2	$4.78 \pm 2.13 \times 10^{-33}$
4.0 - 4.5	3.0	$2.6 \pm 1.7 \times 10^{-33}$
4.5 - 5.0	0.5	$4.4 \pm 7.6 \times 10^{-34}$
		- 4.4

Table 12: +50 GeV/c $pp \rightarrow pp$

$ t $ [(GeV/c) ²]	events	$d\sigma/dt$ [cm ² /(GeV/c) ²]
0.80- 0.85	463	$2.18 \pm 0.14 \times 10^{-29}$
0.85- 0.90	339	$1.38 \pm 0.10 \times 10^{-29}$
0.90- 0.95	293	$1.09 \pm 0.08 \times 10^{-29}$
0.95- 1.00	199	$7.03 \pm 0.62 \times 10^{-30}$
1.0 - 1.1	239	$3.84 \pm 0.33 \times 10^{-30}$
1.1 - 1.2	109	$1.57 \pm 0.19 \times 10^{-30}$
1.2 - 1.3	56	$7.37 \pm 1.32 \times 10^{-31}$
1.3 - 1.4	27	$3.45 \pm 0.84 \times 10^{-31}$
1.4 - 1.5	31	$3.47 \pm 0.78 \times 10^{-31}$
1.5 - 1.6	22	$2.32 \pm 0.65 \times 10^{-31}$
1.6 - 1.8	39	$1.95 \pm 0.37 \times 10^{-31}$
1.8 - 2.0	41	$2.04 \pm 0.35 \times 10^{-31}$
2.0 - 2.4	81	$1.65 \pm 0.20 \times 10^{-31}$
2.4 - 2.8	32	$5.60 \pm 1.11 \times 10^{-32}$
2.8 - 3.2	15	$2.69 \pm 0.79 \times 10^{-32}$
3.2 - 3.6	5.0	$9.4 \pm 5.3 \times 10^{-33}$
3.6 - 4.0	4.0	$7.6 \pm 4.5 \times 10^{-33}$

Table 13: -30 GeV/c $\bar{p}p \rightarrow \pi^-\pi^+$

$ t $ [(GeV/c) ²]	events	$d\sigma/dt$ [cm ² /(GeV/c) ²]	
2.0 - 2.5	0	4.00×10^{-33}	upper limit
2.5 - 3.0	0	2.27×10^{-33}	upper limit
3.0 - 3.5	0	1.86×10^{-33}	upper limit
3.5 - 4.0	0	1.35×10^{-33}	upper limit

Table 14: -50 GeV/c $\bar{p}p \rightarrow \pi^-\pi^+$

$ t $ [(GeV/c) ²]	events	$d\sigma/dt$ [cm ² /(GeV/c) ²]	
2.0 - 2.5	0	3.84×10^{-33}	upper limit
2.5 - 3.0	0	2.32×10^{-33}	upper limit
3.0 - 3.5	0	2.03×10^{-33}	upper limit
3.5 - 4.0	0	1.65×10^{-33}	upper limit

Table 15: -30 GeV/c $\bar{p}p \rightarrow K^-K^+$

$ t $ [(GeV/c) ²]	events	$d\sigma/dt$ [cm ² /(GeV/c) ²]	
2.0 - 2.5	0	2.07×10^{-33}	upper limit
2.5 - 3.0	0	1.36×10^{-33}	upper limit
3.0 - 3.5	0	1.30×10^{-33}	upper limit
3.5 - 4.0	0	1.05×10^{-33}	upper limit

Table 16: $-50 \text{ GeV}/c \quad \bar{p}p \rightarrow K^-K^+$

$ t \text{ [}(\text{GeV}/c)^2\text{]}$	events	$d\sigma/dt \text{ [cm}^2/(\text{GeV}/c)^2\text{]}$
2.0 - 2.5	0	2.38×10^{-33} upper limit
2.5 - 3.0	0	1.82×10^{-33} upper limit
3.0 - 3.5	0	1.63×10^{-33} upper limit
3.5 - 4.0	0	1.48×10^{-33} upper limit

Figure Captions

- Fig.1 Schematic view of the experimental set-up in Period-II.
- Fig.2 χ^2/dof distributions for selected $\bar{p}p$ 30 GeV/c events (a) and pp 50 GeV/c events (b) for three different t -bins. Cuts are marked by arrows. Dashed curves represent the square root fits to the background.
- Fig.3 Coplanarity (a) and $\Delta\theta$ (b) distributions for selected pp 50 GeV/c events for $1.0 < |t| < 1.1$ (GeV/c) 2 . Solid lines are for events with χ^2/dof below the cut; dotted curves (smoothed) are for events with χ^2/dof above the cut.
- Fig.4 The geometrical acceptance of the $\bar{p}p$ 30 GeV/c set-up as a function of $|t|$. Solid curve is for elastic events; dashed and dotted curves are for annihilation events into K^-K^+ and $\pi^-\pi^+$, respectively. The curves have been smoothed.
- Fig.5 χ^2 distributions for selected $\bar{p}p$ 50 GeV/c events for three different t -bins.
- Fig.6 π^-p elastic differential cross section at 20 GeV/c incident momentum (this exp.). The large- $|t|$ ($|t| > 7$ (GeV/c) 2) data are from the earlier large-angle phase of this experiment [6]. The dashed curve is the smoothed π^-p 9.7 GeV/c data from ref.[19]. The CIM fit to the 20 GeV/c data is from ref.[6].
- Fig.7 π^-p elastic differential cross section at 50 GeV/c (this exp.).

Solid curve is the prediction of generalized geometrical scaling [42], obtained by rescaling the unabsorbed overlap function τ_0 from pp data at $\sqrt{s}=52.8$ GeV.

Fig.8 π^+p elastic differential cross section at 50 GeV/c (this exp.). Dashed curve is the prediction of the Chou-Yang model [43] when the pion form factor $F_\pi(q^2)=F_p(q^2)^{2/3}$, as given by the Additive Quark Model, is used. Solid curve indicates $|t|^{-7}$ behaviour.

Fig.9 π^-p elastic differential cross sections at 20 GeV/c (this exp. and [6]), 50 GeV/c ($\times 10^{-1}$) (this exp.) and 200 GeV/c ($\times 10^{-2}$) [22].

Fig.10 K^-p elastic differential cross section at 20 GeV/c (this exp.). The large- $|t|$ ($|t| > 7$ (GeV/c) 2) data are from the earlier large-angle phase of this experiment [6]. Solid curve is the smoothed π^-p 20 GeV/c differential cross section (this exp. and [6]).

Fig.11 K^+p elastic differential cross section at 50 GeV/c (this exp.). Solid curve is the smoothed π^+p 50 GeV/c data of this experiment.

Fig.12 $\sigma_{\text{tot}} \cdot |t|$ versus $1/\sigma_{\text{tot}}^2 \cdot d\sigma/dt$ for πp and Kp elastic scattering between 20 and 200 GeV/c and $1 < |t| < 4$ (GeV/c) 2 (data from this exp. and [22]). Solid line is drawn to mark the separation between πp and Kp .

Fig.13 Generalized geometrical scaling [42] predictions for

K^+p 50 GeV/c (a) and π^+p 50 GeV/c (b) elastic differential cross sections. The predictions are obtained by rescaling the eikonal from pp data at $\sqrt{s}=53$ GeV.

Fig.14 $s^8 \cdot d\sigma/dt$ versus $-t/s$ for π^-p elastic scattering at 20, 50 and 200 GeV/c and $|t| > 5$ (GeV/c)² (data from this exp. and refs. [6,22]). Straight lines indicate $|t|^{-7}$ and $|t|^{-3}$ dependences.

Fig.15 pp elastic differential cross sections at 30 and 50 GeV/c (this exp.). Solid and dashed curves are the differential cross sections calculated in the nucleon core model [30] at 30 and 50 GeV/c, respectively.

Fig.16 $p\bar{p}$ elastic differential cross sections at 30 and 50 GeV/c (this exp.), compared with $p\bar{p}$ data at 5.0 [15], 6.2 [16] and 10.1 [17] GeV/c. The 5.0 and 6.2 GeV/c data are presented as smoothed curves.

Fig.17 pp elastic differential cross sections at 50 GeV/c (this exp.), compared with small- $|t|$ pp data at 50 GeV/c [21], and the $p\bar{p}$ 50 GeV/c data of this experiment. Solid curve is the pp 50 GeV/c differential cross section calculated in the nucleon core model [30].

Fig.18 pp elastic differential cross sections at 24 GeV/c [7], 50 GeV/c (this exp.), 100 GeV/c ($\times 10^{-1}$) [9], 200 GeV/c ($\times 10^{-2}$) [9,10] and $\sqrt{s}=44.6$ GeV ($\times 10^{-3}$) [11].

Fig.19 Fixed- t energy dependence of pp elastic differential cross

sections at $|t|=2, 2.5, 3, 3.6, 4, 6, 8, 10$ and 12 (GeV/c)^2 in the momentum range 9 to 1486 GeV/c (from ref.[4]). Solid curves are eye-fits.

Fig.20 Fixed- t energy dependence of $\bar{p}p$ elastic differential cross sections at $|t| = 2.0$ and 4.0 (GeV/c)^2 in the momentum range 3.6 to 50 GeV/c (from ref.[5]). Straight lines are eye-fits.

WA7 EXPERIMENTAL SET-UP (PERIOD II)

CH0-9 MWPC's

Č1-2 Čerenkov counters

Fig.1

Fig.2

Fig.3

Fig.4

Fig. 5

Fig. 6

Fig.7

Fig.8

Fig. 9

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Fig.14

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Fig.17

Fig.18

Fig.19

Fig.20