ELASTIC SCATTERING AND TOTAL CROSS-SECTIONS:
RECENT EXPERIMENTAL RESULTS

T. Ekelöf
CERN, Geneva, Switzerland
ELASTIC SCATTERING AND TOTAL CROSS-SECTIONS:
RECENT EXPERIMENTAL RESULTS.

T. Ekelöf
CERN, Geneva, Switzerland

INTRODUCTION

In the field of elastic scattering and total cross-sections the antiproton source at CERN has opened up new ground for experimental exploration. Firstly, the CERN p̅p Collider has allowed measurements of proton interactions at an equivalent beam energy which is nearly two orders of magnitude higher than that available earlier at the Intersecting Storage Rings (ISR). Secondly, filling one of the ISR rings with antiprotons has made it possible to measure p̅p interactions in the ISR energy range, which can be compared in detail with the results of pp measurements already obtained earlier. At this conference we can enjoy the fruits of efforts made in these directions.

In addition, some enlightening results are reported from an SPS experiment at 30 GeV/c. Although this energy may seem far from that of the ISR and the p̅p Collider, the outcome of these new measurements has in fact some interesting implications for the interpretation of the data from the ISR and the p̅p Collider.

PROTON–ANTIPROTON COLLIDER RESULTS

Two small-angle scattering experiments have been set up at the p̅p Collider. One is a dedicated experiment of the UA4 Collaboration\textsuperscript{1,2} set up at the same intersection as another collider experiment (UA2), and the other is an integrated part of the detector of the UA1 Collaboration\textsuperscript{3}. Both use the same basic strategy as was used for the pp small-angle scattering measurements at the ISR in the 1970's by the CERN–Rome Collaboration\textsuperscript{4}. The strategy involves the use of special indents in the accelerator vacuum-chamber, called Roman pots, in order to bring the track detectors as close as possible to the circulating beams. A new feature is that the scintillator hodoscopes used as track detectors at the ISR have been exchanged against high-precision drift chambers read out with charge division. Furthermore, in the UA4 experiment the number of measuring stations (pots) is doubled, thus increasing the redundancy in the measurement and also allowing the quadrupoles in the machine lattice to be used for measuring the particle momentum. In the UA4 experiment, as at the ISR, the apertures at larger angles in the forward-backward directions are covered with special counters with sufficient span in rapidity to make possible an accurate measurement of the inelastic interaction rate.
Both $p\bar{p}$ Collider experiments had preliminary runs in 1981\textsuperscript{5,6).} In 1982, more statistics were collected by both experiments in one run with the $p\bar{p}$ Collider operated in a special high-$\beta$ mode (allowing data-taking at very low $|t|$-values down to $|t| = 0.03$ GeV\textsuperscript{2}), and one run with the machine in an intermediate-$\beta$ mode ($0.2 < |t| < 0.5$ GeV\textsuperscript{2}). In addition, UA4 took data under ordinary low-$\beta$ conditions ($0.4 < |t| < 1.6$ GeV\textsuperscript{2}). The results of these runs are now available\textsuperscript{1-3).} During the spring of 1983, UA4 had a large-statistics run at high $\beta$ and continued to take data at low $\beta$. The analysis of these later UA4 data is still in progress.

From the measured $(d\sigma/dt)_{el}$ distributions at low $t$, the optical point

$$ (d\sigma/dt)_{t=0} = \frac{1 + \rho^2}{16\pi} \sigma_{tot}^2 $$

(1)

can be obtained by extrapolation to $t = 0$, thus providing a measurement of the total cross-section [or rather $\sigma_{tot}(1+\rho^2)$]. However, to obtain a normalized $d\sigma/dt$ from the measured elastic rate $dR_{el}/dt$, the integrated luminosity $\mathcal{L}$ must be determined:

$$ d\sigma/dt = (dR_{el}/dt)/\mathcal{L} $$

(2)

In UA1 this was done by measuring the profiles and intensities of the colliding beams. In UA4 the measurement of the inelastic rate $R_{inel}$ was used, together with the integral of the measured elastic rate $R_{el}$, to derive the total interaction rate $R_{tot}$:

$$ R_{tot} = R_{inel} + R_{el} = \mathcal{L} \cdot \sigma_{tot}. $$

(3)

Eliminating $\mathcal{L}$ in Eqs. (1), (2), and (3) yields

$$ \sigma_{tot} = \frac{16\pi}{1 + \rho^2} \frac{(dR_{el}/dt)_{t=0}}{R_{tot}} $$

(4)

The results of the $\sigma_{tot}$ measurements thus obtained are

- UA1: $\sigma_{tot}(1+\rho^2) = 67.6 \pm 5.9 \pm 2.7$ mb,
- UA4: $\sigma_{tot}(1+\rho^2) = 71.0 \pm 7.0$ mb.

As indicated explicitly in the UA1 case, the statistical errors dominate over the systematic ones in the present situation. This is due to the strong limitation in the statistics collected in the high-$\beta$/low-$t$ mode (half a day of machine time only). During the UA4 runs in the spring of 1983, the statistics in this $t$ region were increased by more than an order of magnitude, and the error in the total cross-section measurement can therefore by expected to decrease accordingly in the near future.

The results of the two experiments are plotted in Fig. 1 together with a dispersion relation prediction\textsuperscript{4) based on data at lower energies. The new data are compatible with an energy dependence of $\sigma_{tot}$ that corresponds to the maximum growth ln\textsuperscript{2} s allowed by the Froissard bound. However, a linear ln s behaviour cannot be excluded by the present data. The results of the on-going analysis of the more recent UA4 measurements will, however, most probably allow a more stringent bound to be set on this energy behaviour.
Also the observed t-behaviour of the $(d\sigma/dt)_{\text{el}}$ shows several remarkable features. First, the $d\sigma/dt$ slope at $|t|$-values above 0.2 GeV$^2$ was found to be higher than what was generally expected:

\[
\begin{align*}
\text{UA1} : & \quad b = 17.1 \pm 1.0 \text{ GeV}^{-2}; \\
& \quad 0.04 < -t < 0.18 \text{ GeV}^2; \\
\text{UA4} : & \quad b = 17.6 \pm 1.0 \text{ GeV}^{-2}; \\
& \quad 0.03 < -t < 0.19 \text{ GeV}^2.
\end{align*}
\]

As shown in Fig. 2, this represents a rise of about 4 units (GeV$^{-2}$) from the values observed at the highest ISR energies. Also in this case it is difficult to discriminate between a $\ln^2 s$ or a $\ln s$ behaviour of $b$ with $s$, partially because of inconsistencies between data from different experiments in the region at lower energies ($\sqrt{s} = 15-30$ GeV). The line shown in Fig. 2 is a prediction\textsuperscript{7} based on lower-energy data containing both a $\ln s$ and a $\ln^2 s$ term.

In the intermediate region $0.2 < -t < 0.7$ GeV$^2$ the results of the slope measurements are:

\[
\begin{align*}
\text{UA1} : & \quad b = 13.7 \pm 0.2 \text{ GeV}^{-2}; \\
& \quad 0.21 < -t < 0.55 \text{ GeV}^2; \\
\text{UA4} : & \quad b = 13.7 \pm 0.2 \text{ GeV}^{-2}; \\
& \quad 0.21 < -t < 0.50 \text{ GeV}^2; \\
& \quad b = 13.6 \pm 0.2 \text{ GeV}^{-2}; \\
& \quad 0.49 < -t < 0.75 \text{ GeV}^2.
\end{align*}
\]

This represents an increase of about 2 units (GeV$^{-2}$) from the values found at the highest ISR energies, as illustrated in Fig. 3. As before, the $s$ behaviour is difficult to determine. It is, however, worth noting in this context that according to a recently demonstrated theorem by Martin\textsuperscript{9}, if the total cross-section rises as $\ln^2 s$, and if the ratio $\sigma_{\text{el}}/\sigma_{\text{tot}}$ tends to a non-zero value, then at asymptotic energies and at $t = 0$ also $b$ should rise as $\ln^2 s$; on the other hand, for $t < 0$, $b$ should not grow more quickly than $\ln s$. It is interesting to compare the difference between the behaviour of the shrinkage at
Fig. 2 The \( (d\sigma/dt)_{t=0} \) slope \( b \) for \( p\bar{p} \) scattering in the \( |t| \) range 0.05–0.2 GeV\(^2\) as measured by the UA1 and UA4 experiments. The upper UA4 point represents the 1982 run; the lower one, the 1981 run. The line shows a prediction\(^7\) based on lower energy data.

Fig. 3 The \( (d\sigma/dt)_{t=0} \) slope \( b \) for \( p\bar{p} \) scattering in the \( |t| \) range 0.2–0.5 GeV\(^2\) as measured by the UA1 and UA4 experiments. The lines show a prediction\(^8\) based on a simultaneous fit to \( pp \) and \( p\bar{p} \) data at lower energies.

Fig. 4 Plot showing \( (d\sigma/dt)_{t=0} \) for \( p\bar{p} \) scattering at the Collider (\( \sqrt{s} = 540 \) GeV) as measured by the UA4 experiment (there is a line through the points to guide the eye) and for \( pp \) scattering at the ISR (\( \sqrt{s} = 53 \) GeV)\(^9\) (no line through the points).
low t-values and that at intermediate t-values as measured at the Collider, with this theorem. The lines shown in Fig. 3 correspond to a simultaneous fit\(^9\) to pp and p\(\bar{p}\) data at lower energies. This fit happens to be based on a linear \(\ln s\) behaviour at high energies.

In the high-t region the inelastic background is substantial, and therefore momentum analysis is required in the event selection. This could be done in the UA4 experiment only. The analysis of these data is preliminary, but clearly shows a rather flat shoulder in the \(d\sigma/dt\) distribution above \(|t| = 0.8\ \text{GeV}^2\), as is shown in Fig. 4 (points followed by a line to guide the eye). In this figure there has also been plotted the highest-energy pp (note: not p\(\bar{p}\)) data from the ISR\(^{10}\) (no line) showing, in this case, a clear dip between the slope and the shoulder.

The p\(\bar{p}\) shoulder (Collider data) starts at a lower \(|t|\) value (0.8 instead of 1.3 GeV\(^2\)) and has a level which is at least an order of magnitude higher than that of the ISR data. These new results have had a strong impact on the various theoretical models describing elastic scattering at high energy. In particular, the results seem to be in clear disagreement with the predictions of the Reggeon field theory\(^{11}\) and those of the Chou-Yang\(^{12}\) model.

**ISNR RESULTS**

Two different experiments at the ISR have made measurements of the p\(\bar{p}\), and, for reference, the pp total cross-section. The first, carried out by the CERN-Louvain-Northwestern-Utrecht Collaboration (R221)\(^{13-15}\) uses the Roman pot technique with scintillator hodoscopes to measure low-t elastic scattering in a set-up very similar to that used in the earlier CERN-Rome experiment\(^6\). The second experiment, carried out by the CERN-Naples-Pisa-Stony Brook Collaboration (R210)\(^{16-18}\), uses the total interaction technique in which the total interaction rate \(R_{\text{tot}}\) and the luminosity \(\mathcal{L}\) are measured simultaneously (\(\sigma_{\text{tot}} = R_{\text{tot}}/\mathcal{L}\)). This method has also been used earlier at the ISR for pp measurements by the Pisa-Stony Brook Collaboration\(^{19}\). The results of these experiments, most of which have now been published\(^{13-18}\), show that \(\sigma_{\text{tot}}\) for pp is rising in the ISR energy range, as illustrated in Fig. 5, and that the difference \(\Delta\sigma = \sigma_{\text{tot}}(p\bar{p}) - \sigma_{\text{tot}}(\text{pp})\) continues to decrease as expected from the behaviour at lower energies\(^{20,21}\), as shown in Fig. 6 [the latter result apparently obviates the need for any kind of the so-called odderon\(^{22,23}\)]. Comparing\(^{18}\) the old measurements of \(\sigma_{\text{tot}}(\text{pp})\) and the new, repeated measurements of the same quantity, has given an indication that there may be a systematic difference between the results obtained with the total interaction method.

---

*Fig. 5 Data on the p\(\bar{p}\) and pp total cross-sections from measurements at the ISR, shown together with data at lower energies. The curves represent fits\(^{18}\) to the data that include the new measurements (except the R211 data).*
Fig. 6  The difference $\Delta \sigma = \sigma_{\text{tot}}(p\bar{p}) - \sigma_{\text{tot}}(pp)$ as obtained from data available up to ISR energies. The lines represent fits to the data at lower energy (dashed line Ref. 20, full line Ref. 21).

Fig. 7  Plot showing the measurements of the $p\bar{p}$ and $pp$ real part at the ISR together with data at lower energies. The curves correspond to a dispersion relation prediction made before the new $p\bar{p}$ measurements became available.

and those obtained with the optical theorem method at the highest ISR energy ($\sqrt{s} = 62 \text{ GeV}$). This question will require some clarification.

In the low-$t$ elastic scattering experiment (R211), the real part $\rho$ of the $p\bar{p}$ amplitude has also been determined. The results obtained are shown in Fig. 7. Both the results on $\sigma_{\text{tot}}$ and those on $\rho$ for $p\bar{p}$ confirm closely the earlier dispersion relation predictions made for these quantities. These predictions were based on the previous $pp$ measurements at the ISR and other lower energy $pp$ and $p\bar{p}$ data.

New results on $p\bar{p}$ and $pp$ elastic scattering are reported at this conference by the Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration working at the Split-Field Magnet (SFM) spectrometer at the ISR. Measurements were made at centre-of-mass energies $\sqrt{s} = 31$, 53, and 62 GeV, and the $d\sigma/dt$ data have allowed an accurate determination of the nuclear slope parameter $b$ in the region up to $-t = 0.8 \text{ GeV}^2$. The data collected at $\sqrt{s} = 31 \text{ GeV}$, which cover the $t$ region down to $-t = 0.05 \text{ GeV}^2$, show that there is a change in $b$, as a function of $t$, of roughly two units (GeV$^{-2}$) around $-t = 0.15 \text{ GeV}^2$ in $p\bar{p}$ scattering, similar to what has been observed earlier in $pp$ scattering. At $\sqrt{s} = 53 \text{ GeV}$ and $62 \text{ GeV}$, data were obtained down to $-t = 0.11$ and $0.17 \text{ GeV}^2$ respectively. The slope in the region $0.2 < -t < 0.8 \text{ GeV}^2$, which is well fitted by a single exponential at all three
energies, is found to increase over the ISR energy, as shown by the open circles in Fig. 8b. As this figure also shows, the $p\bar{p}$ slope approaches the pp slope (filled circles) as the energy increases, leading to a decrease of the difference $\Delta b = b_{p\bar{p}} - b_{pp}$ from $\Delta b = 0.58 \pm 0.15$ GeV$^{-2}$ at $\sqrt{s} = 31$ GeV to $\Delta b = 0.26 \pm 0.16$ GeV$^{-2}$ at $\sqrt{s} = 62$ GeV. Figure 8a shows that the same trend is confirmed at low $t$ by the $p\bar{p}$ and pp slope determination at $\sqrt{s} = 31$ GeV.

A compilation$^{24}$ of the $p\bar{p}$ and pp data on $\sigma_{tot}$, b, and $\sigma_{el}$ from these three ISR experiments shows that $\sigma_{el}/\sigma_{tot} = 0.175$ and $b/\sigma_{tot} = 0.30$ mb$^{-1}$ GeV$^{-2}$, almost independently of energy and particle. The UA4 experiment reports these ratios to be $\sigma_{el}/\sigma_{tot} = 0.20 \pm 0.02$ and $b/\sigma_{tot} = 0.26 \pm 0.03$ mb$^{-1}$ GeV$^{-2}$ for $p\bar{p}$ scattering at $\sqrt{s} = 280$ GeV. The constancy of these ratios with energy over such a wide energy range implies a consistency with the simple picture of geometrical scaling which is remarkable!

SPS FIXED-TARGET RESULTS

Much of the interest in the physics of elastic scattering and total cross-sections lies in the $s$-dependence of these quantities measured over large energy ranges (illustrated by the fact that the relevant parameter in most models is log $s$ rather than $s$). Therefore, although we now start to get precise data on pp interactions at pp Collider energies ($p_{lab} = 146,000$ GeV), new data at the lower end of the SPS fixed-target energy range ($p_{lab} = 30$ GeV), are also of primary interest. New results at 30 GeV are reported at this conference by the Annecy (LAPP)-CERN-Copenhagen (NBI)-Oslo-Genoa-London (UC) Collaboration (WA7)$^{25}$ on pp elastic scattering in the range $0.5 < -t < 5.8$ GeV$^2$. The same group has earlier reported$^{26-27}$ measurements on both pp and $p\bar{p}$ at 50 GeV/c. The experimental set-up consists of a liquid-hydrogen target followed by a two-arm spectrometer that measures both the scattered beam particle and the recoiling target proton. Figure 9 shows the pp results at 30 and 50 GeV together with data from earlier experiments at 5, 6.2, and 10 GeV. In the low-energy data, two dip structures are seen at about $-t = 0.5$ GeV$^2$ and $-t = 2$ GeV$^2$, whereas in the 50 GeV data, only one dip is seen around $-t = 1.5$ GeV$^2$. The very important question answered by the new data at 30 GeV is whether the dip in the 50 GeV
Fig. 9 The new data on \( (d\sigma/dt)_{el} \) for \( p\bar{p} \) scattering at 30 GeV, shown together with the results of earlier measurements at 5, 6.2, 10, and 50 GeV.

case is a result of the \(-t = 0.5 \text{ GeV}^2\) dip in the low-energy data moving towards higher \(t\) with increasing energy, or of the \(-t = 2 \text{ GeV}^2\) dip moving towards lower \(t\). Since in the 30 GeV case the dip occurs at \(-t = 1.7 \text{ GeV}^2\) the latter hypothesis must clearly be the correct one. This conclusion is further reinforced by the indication of a change of slope in the 30 GeV data at \(-t = 0.8 \text{ GeV}^2\), interpreted as the remainder of the \(-t = 0.5 \text{ GeV}^2\) dip at lower energies.

CONCLUDING REMARKS

The results of the \( p\bar{p} \) measurements at 30 GeV rule out the validity at this energy of the Chou and Yang model\(^{28}\) as well as that of the geometrical scaling model\(^{29}\), since in both these the diffraction dip is required to move outwards with increasing energy (since \( C_{\text{tot}}(p\bar{p}) \) decreases at these energies). Other models, such as the nucleon core model of Guillaud and Islam\(^{10-32}\) and the Donnachie-Landshoff model\(^{33}\), predict the right direction of the dip movement and also describe the data reasonably well quantitatively.

The Chou-Yang model also fails to describe the high slope and the shallow dip (shoulder) for \( p\bar{p} \) scattering at Collider energies. At these energies, as well as for \( pp \) scattering at the ISR, the geometrical scaling model fits the data reasonably well. This is also true for the nucleon core model and the Donnachie-Landshoff model.

Although the latter two models are very different in nature, they both reproduce the behaviour of the available \( pp \) and \( p\bar{p} \) data over a very wide energy range from 30 to 146,000 GeV. On the other hand, the two models make very different predictions for the shape of the \( d\sigma/dt \) structure at high \( t \) to be expected in \( p\bar{p} \) scattering at the ISR: the nucleon core model predicts a pronounced dip/bump structure, whereas the Donnachie-Landshoff model predicts a shoulder similar in shape to what is seen for \( p\bar{p} \) scattering at the \( p\bar{p} \) Collider. In order to arbitrate between these two models it is thus of great importance that the SFM experiment on elastic scattering is given the opportunity to extend the \( p\bar{p} \) measurements up to at least \(-t = 1.5 \text{ GeV}^2\) before the ISR operation is terminated.
It will be equally exciting to see the results of the final analysis of the UA4 runs, including those of spring 1983. One important aim is to further consolidate the height of the \(d\sigma/dt\) shoulder in the \(t\)-range above \(t = 0.8 \text{ GeV}^2\) since, also in this case, the various models that have survived so far differ in their predictions with regard to this height. Furthermore, clearly the determination of \(\sigma_{\text{tot}}(pp)\) to a precision of \(\pm 1 \text{ mb}\) at the \(p\bar{p}\) Collider will have a great impact on our ideas about the asymptotic \(pp\) behaviour.

A more remote possibility is that the UA4 experiment will be run with the Collider operated in pulsed mode, thus spanning the full SPS energy range in collision mode. This would allow measurements of \(d\sigma/dt\) and \(\sigma_{\text{tot}}\) up to \(\sqrt{s} = 900 \text{ GeV} (p_{\text{lab}} = 400,000 \text{ GeV})\) and possibly also some determination of the real part of the elastic amplitude in the lower end of this energy range where Coulomb scattering could become experimentally accessible. If so, dispersion relations would then possibly help us to predict the behaviour of \(\sigma_{\text{tot}}\) at even higher energies than \(p_{\text{lab}} = 400,000 \text{ GeV}\) -- a prodigious prospect indeed!

**REFERENCES**

1. M. Bozzo et al., (UA4 Collaboration), Proton-antiproton total cross-sections at \(\sqrt{s} = 540 \text{ eV}\), Paper 0117 submitted to this conference.


18. T. Del Prete, Measurements of total cross-section in proton-proton and proton-antiproton collisions at ISR energies, Talk given at the Moriond Workshop on Antiproton-Proton Physics, La Plagne, Savoie, France, 1983.

