ELASTIC SCATTERING AND TOTAL CROSS SECTION

AT THE CERN SPS COLLIDER

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ABSTRACT

Recent results of the UA4 experiment on proton-antiproton low-t elastic scattering and total cross section at $\sqrt{s} = 546$ GeV are presented. Implications for the theoretical models of high-energy collisions and expectations at higher energies are also discussed.

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Proton-antiproton elastic scattering was measured at the CERN SPS collider ($\sqrt{s} = 546$ GeV) using a system of "Roman pots" and a specially designed high $\beta$ beam optics which allowed detecting events down to scattering angles of 0.5 mrad [1]. Elastic events are identified by requiring the collinearity of the two scattered particles. The width of the collinearity distributions provides a direct measurement of the momentum transfer resolution which was found to be $\Delta t = 0.006 \sqrt{-t}$. This very good resolution implies that no smearing correction has to be applied to the data. In the present experiment data were taken in the momentum transfer range $0.03 < -t < 0.32$ GeV$^2$, collecting a sample of about $10^5$ elastic events. These data supersede previous measurements with much less statistics [2]. The measured differential cross section is shown in fig. 1(a) together with previous data [3] in the range $0.21 < -t < 0.5$ GeV$^2$, which were normalized to the present data in the overlapping region.

From the study of the $t$-dependence it was found that for $-t < 0.15$ GeV$^2$ the data can be well described by a single exponential $\exp(bt)$. The same is true in the range $-t > 0.2$ GeV$^2$. The slope parameter $b$ has, however, quite different values in the two regions, $b = 15.3 \pm 0.3$ GeV$^{-2}$ for $0.03 < -t < 0.10$ GeV$^2$ and $b = 13.4 \pm 0.3$ GeV$^{-2}$ for $0.21 < -t < 0.5$ GeV$^2$. A rapid change of the local slope parameter takes place between these two regions of momentum transfer. A fit of the data with two constant slopes leaving also as free parameter the $t$-value $t_0$, where the sudden change of slope occurs, gives the result $-t_0 = 0.14 \pm 0.02$ GeV$^2$. The exponential form with quadratic $t$-dependence, $\exp(Bt + Ct^2)$, is not a good parametrization of the data. Fits for $-t < 0.15$ GeV$^2$ give values of $C$ which are compatible with zero. A significant quadratic dependence can only be obtained by fitting the data over a $t$-region which extends up to at least 0.3 GeV$^2$ but the linear decrease of the slope with $t$, $b(t) = B - 2C|t|$, appears to be not consistent with the observed values of the local slope as obtained by using the exponential fit $\exp(bt)$ in restricted $t$-intervals. This behaviour of the collider data is very similar to that observed at the ISR [4], where a change of slope was found around $-t = 0.1$ GeV$^2$.

As the energy increases from the ISR to the SPS collider the overall $t$-distribution of elastic scattering in the diffraction peak region
shrinks. The shape of the distribution, however, keeps the feature of a rapid variation of the slope between 0.1 and 0.2 GeV^2. The energy dependence of the "forward" slope (-t < 0.1 GeV^2) is shown in fig. 1(b). Data on the local slope b(t) as measured in various t-intervals at the collider and at the ISR (pp scattering at \(\sqrt{s} = 53\) GeV) are presented in fig. 2.

The total cross section \(\sigma_t\) was obtained [5] from the measurement of low-t elastic scattering and of the inelastic interaction rate, making use of the optical theorem. This method does not require the knowledge of the machine luminosity and provides a measurement of the quantity \((1 + \rho^2)\sigma_t\), where \(\rho\) is the ratio of the real to the imaginary part of the forward elastic amplitude. The measurement of the inelastic rate was performed by a system with almost complete solid angle coverage using a fully inclusive trigger. Events having the special topology of diffractive dissociation were included in the trigger. Vertex reconstruction allowed clear identification of beam-beam interactions. The fraction of the inelastic events which were missed because all particles are confined inside the beam pipe was estimated to be not more than 1%.

The result of the measurement is \((1 + \rho^2)\sigma_t = 63.3 \pm 1.5\) mb. Using the value \(\rho = 0.15\) as suggested by the dispersion relation fit of ref. [6] and by the more recent fit of ref. [7], the result on the total cross section is \(\sigma_t = 61.9 \pm 1.5\) mb. The uncertainty on the estimate of \(\rho\) reflects in a change of the value of \(\sigma_t\) which is well inside the quoted error. The collider result is shown in fig. 3 together with pp and pp data at lower energies. Using the elastic scattering data and a determination of the machine luminosity (affected by a 10% systematic error) the result \(\sigma_t = 61 \pm 3\) mb was obtained, which agrees with the more accurate measurement from the luminosity independent method. The elastic cross section is \(\sigma_{el} = 13.3 \pm 0.6\) mb, while the ratio \(\sigma_{el}/\sigma_t\) which is independent of any assumption on the real part is equal to \(0.215 \pm 0.005\). These results are shown in fig. 4, together with lower energy data.

As discussed in ref. [5] a fit to the pp and pp total cross section data of fig. 3 using the logarithmic term (\(\log s\))^Y in addition to the usual
power terms needed to describe the low-energy region, gave the result  
\( \gamma = 1.9 \pm 0.1 \). This indicates that the total cross section rises in the
presently explored energy range in a way which is already close to the
\((\log s)^2\) behaviour of the Froissart bound. The ratio \( \sigma_{el}/\sigma_t \) is definitely
larger at the collider than at the ISR, where it is nearly constant around
0.175.

The energy dependence of \( \sigma_{el}/\sigma_t \) is crucial for the understanding of
the high-energy behaviour of hadron-hadron scattering and allows a clear
discrimination between different theoretical approaches [8]. Regge field
theory with critical Pomeron predicts that the ratio \( \sigma_{el}/\sigma_t \) should slowly
decrease asymptotically. In the "geometrical scaling" model [9], the
scaling law of the elastic amplitude in terms of the variable \( t_0/t \), which
is valid asymptotically if the Froissart bound is saturated [10], is
assumed to hold already at present energies, leading then to the
prediction \( \sigma_{el}/\sigma_t = \text{const} \). Both these predictions are not confirmed by
the collider data.

The experimental results agree, at least qualitatively, with the
prediction of the model by Cheng and Wu [11] and with the idea which is
underlying the model by Chou and Yang [12]. The trend of the data seems
to suggest (or is at least compatible with) the following scenario. In
the present energy range proton-proton scattering is in a "transition
regime", where \( \sigma_t \) increases with a dependence close to \((\log s)^2\) and the
ratio \( \sigma_{el}/\sigma_t \) has started to rise. Eventually, at higher energies, the
"asymptotic regime" may take over where \( \sigma_t \) saturates the Froissart bound and
\( \sigma_{el}/\sigma_t \) approaches a constant value, possibly 1/2. This behaviour can be
translated in the impact parameter language by saying that the proton
expands with energy, becoming also more absorbing in the central region of
low impact parameter. At present energies the extension of the central
region is comparable in size to the "diffuseness", or peripheral region.
At higher energies, however, the peripheral region will become less and
less important if the proton "radius" expands logarithmically with
energy. The analysis of the \( t \)-dependence of the differential cross
section up to the region of the second maximum [13], confirms that this is
indeed the trend of the data in the energy region from the ISR to the SPS
collider.
The first indication of the approach to the "asymptotic regime" came from the ISR discovery of the rising total cross sections, which is complemented now by the collider observation of the increase of the ratio $\sigma_{el}/\sigma_t$.

The collider results on elastic scattering and total cross section have been discussed recently in several papers. The basic motivations of the various approaches are often similar. It was shown [14-15] that the ISR and collider data can be described using the impact picture model, which is inspired by the theoretical considerations of ref. [11]. The $t$-dependence of the differential cross section at the collider can be understood in the Glauber multiple diffraction theory [16], using the proton electromagnetic form factor to evaluate the proton opacity, as suggested a long time ago [17]. A Regge type model which includes a three-gluon exchange contribution to account for large $t$ scattering has been developed [18]. Another model [19] that uses a $\ln s$ term in the elastic amplitude in addition to the usual Regge terms, describes the energy dependence of $\sigma_t$ and of low-$t$ scattering correctly.

Expectations for the total cross section at higher energies are presented in fig. 5. The solid line corresponds to the fit of ref. [5], that predicts $\sigma_t = 110$ mb at $\sqrt{s} = 20$ TeV (the energy of the proton collider which could be built inside the LEP tunnel). At this same energy, the model of ref. [14] predicts $\sigma_t = 110$ mb and that of ref. [19], $\sigma_t = 130$ mb. A fit by Martin [20] to the data on total cross section and $\rho$, assuming a $(\ln s)^2$ dependence gives $\sigma_t = 130$ mb at $\sqrt{s} = 20$ TeV (dashed line in fig. 5). An asymptotically constant total cross section cannot, of course, be excluded by the data, as illustrated by the dotted line of fig. 5, which represents a fit [20] with energy dependence close to $(\ln s)^2$ in the energy region of present accelerators. Discriminating between these two hypotheses (dashed and dotted line in fig. 5), which cannot be distinguished on the basis of the available data, is possible by means of a measurement of the real part. For the two hypotheses, the parameter $\rho$ assumes values which differ by $\sim 30\%$ at $\sqrt{s} = 546$ GeV [20].

Both models of refs [14] and [19] predict a slow rise of the ratio $\sigma_{el}/\sigma_t$ with energy, the value expected at $\sqrt{s} = 20$ TeV being $\sim 0.28$. 
Predictions on the slope parameter at higher energies are shown in fig. 6. The solid line refers to the forward slope [19], and the dotted line to the average slope for $-t < 0.15 \text{ GeV}^2$ [14].

We may conclude that several models, relying on basic principles and intuitive physical pictures are able to describe the data correctly, but as a final comment, we sadly remark that a dynamical interpretation in terms of a fundamental theory of the strong interactions is missing at present.
REFERENCES


FIGURE CAPTIONS

Fig. 1  (a) Differential cross section of proton-antiproton elastic scattering at $\sqrt{s} = 564$ GeV from ref. [1].
         (b) The "forward" slope parameter at the collider compared to pp and $\bar{p}p$ results at lower energies.

Fig. 2  The dependence of the local slope parameter on t. The horizontal bar indicates the t interval where the \text{exp}(bt) fit was performed:
         (a) The UA4 results at the collider;
         (b) Compilation for pp scattering at $\sqrt{s} = 53$ GeV.

Fig. 3  The collider result on the $\bar{p}p$ total cross section at $\sqrt{s} = 546$ GeV is shown together with lower energy $\bar{p}p$ and pp data.

Fig. 4  (a) The elastic cross section;
         (b) The ratio of the elastic to the total cross section.

Fig. 5  Extrapolation of the total cross section at higher energies. The dashed and dotted lines are from Martin [20], while the solid line is from ref. [5].

Fig. 6  Predictions on the energy dependence of the slope parameter [14,19].
\[ \text{pp} \]

\[ \sqrt{s} = 5.46 \text{ GeV} \]

- Amos 1983
- Ambrosio 1982
- Breakstone 1983
- Baksa 1978
- De Kerret 1977
- Barellelli 1972
- Arradi 1971
$\sigma_f$ (mb)

$\sqrt{s}$ (GeV)

- $pp\bar{p}$ Serpukhov (ref. 10)
- FNAL
- ISR (1979) " 11
- ISR (R210) " 12
- ISR (R211) " 13
- This experiment (UA4)

Fig. 3
Fig. 4
\[ \sigma_t \sim (\log s)^2 \]

\[ \sigma_t \rightarrow \text{const} \]

Fig. 5