MEASUREMENT OF THE PROTON-ANTIPROTON ELASTIC AND TOTAL CROSS SECTION

AT A CENTRE-OF-MASS ENERGY OF 540 GeV

UA4 Collaboration

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ABSTRACT

First results on the measurement of the elastic and total cross section at the CERN $p\bar{p}$ Collider are presented. Combining the measurement of elastic scattering at low momentum transfer with the rate of inelastic interactions, a value of the total cross section of 66 mb with a 10% statistical error was obtained.

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Measurements of elastic scattering at low momentum transfer [1] and of the total cross section were performed during the first physics run of the CERN proton-antiproton Collider at $\sqrt{s} = 540$ GeV. Data were taken during about 15 hours of running time with an antiproton bunch of $\sim 4 \times 10^9$ particles colliding against a proton bunch of $\sim 5 \times 10^{10}$ particles. The machine optics in the intersection region was the same as for normal SPS operation. The nominal luminosity was of the order of $10^{26} \text{ cm}^{-2} \text{ s}^{-1}$.

The total cross section σ_{tot} is obtained by means of a method pioneered at the ISR [2]. It is based on the simultaneous measurement of low- t elastic scattering and of the total inelastic rate. By using the optical theorem one can write the differential elastic rate at low t as

$$\frac{dN_{\text{el}}}{dt} = L \frac{\sigma_{\text{tot}}^2 (1 + \rho^2)}{16\pi(\hbar c)^2} \exp(bt)$$

where ρ is the ratio of the real to the imaginary part of the forward elastic scattering amplitude and L is the machine luminosity. Moreover,

$$N_{\text{el}} + N_{\text{in}} = L \sigma_{\text{tot}}$$

where N_{el} and N_{in} are the elastic and inelastic rates, respectively. Combining the two previous expressions gives

$$\sigma_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1 + \rho^2} \frac{\left[\frac{dN_{\text{el}}}{dt} \right]_{t=0}}{N_{\text{el}} + N_{\text{in}}} . \quad (1)$$

The total cross section can thus be obtained without the need of an independent determination of the machine luminosity. At present this method provides the only possibility of measuring the total cross section reliably because an accurate measurement of the luminosity is not available at the Collider.

Elastic scattering was measured by a system of four telescopes placed symmetrically above and below the SPS vacuum chamber at a distance of about 40 m from the crossing point. A telescope is composed of two detectors that are 6 m apart. Each detector consists of a high accuracy wire chamber and a scintillation counter hodoscope.

Elastic scattering events were identified by the collinearity requirement. A sample of 1480 elastic events was collected in the range $0.05 < -t < 0.19 \text{ GeV}^2$. The resulting t distribution could be fitted by the exponential shape $\exp(bt)$ with $b = 17.2 \pm 1.0 \text{ GeV}^{-2}$. Details on the elastic scattering measurement are given in ref. [1].

Inelastic interactions are observed in a vertex detector (fig. 1) consisting of two identical systems of three telescopes (D_1 , D_2 and D_3) placed symmetrically on the left and right sides of the crossing region and covering angles from $\sim 0.5^\circ$ to $\sim 10^\circ$. The range in the pseudo-rapidity variable η covered by these detectors is from 2.5 up to 5.6, while the beam rapidity is 6.3. Each telescope is composed of six drift chamber planes backed by a plane of trigger counters (T_1 , T_2 and T_3 , respectively) of full azimuthal coverage. The coordinate along the drift wire is measured by means of a delay line close to the drift wire itself [3], thus yielding the coordinates of a space point directly. This arrangement leads to considerable simplification of the procedure of pattern recognition. The readout of the delay line at both ends provides a constraint that facilitates handling of multiple hits. During data taking the r.m.s. values of the spatial accuracy for the drift and delay line measurements were found to be about 0.4 mm and 4 mm respectively, including the uncertainties in calibrations and in the geometrical survey.

For both elastic and inelastic events, the trigger logic was timed with respect to a gate signal synchronous with the bunch crossing in the intersection region. It was ensured that the elastic and inelastic rates were obtained at the same luminosity by alternately enabling the two triggers. The number of bunch crossings between the enabling and the occurrence of a trigger was recorded. The average rates of elastic and inelastic events were obtained from the total live times of the elastic and inelastic triggers respectively.

Data were mainly taken with two inelastic triggers using the trigger planes T_2 and T_3 :

- (a) A double-arm trigger (left-right coincidence), covering 2.6 units of rapidity on each side ($3.0 < |\eta| < 5.6$), which is expected to detect most of the non-diffractive inelastic events.

- (b) A single-arm trigger, covering the range $3.0 < \eta < 5.6$ on the outgoing $\bar{p}$ side, which allows detection of events that escape the double-arm trigger, in particular single diffractive interactions. The $\bar{p}$ side was chosen because it was less affected by background; the observed rate was then multiplied by two. As a check of this trigger, a low statistics run was taken with a special diffractive trigger defined as the coincidence between an elastic arm and the opposite inelastic arm. The rate and topology of the events collected in this run were in satisfactory agreement with the results of the single-arm trigger.

The following procedure was used to identify inelastic interactions. Events were rejected if the time-of-flight analysis showed that a trigger plane was hit by a halo particle accompanying the incoming beams. This selection caused a 0.2% loss of true beam-beam interactions. A vertex search was then performed on the remaining events. Tracks were reconstructed in the D_1 , D_2 and D_3 telescopes with the requirement that at least four out of six planes contributed a track point. The longitudinal and transverse distributions of reconstructed vertices are shown in fig. 2. The accuracy in the determination of the vertex position (~ 1 cm in the transverse plane and ~ 10 cm in the longitudinal direction) was adequate to identify beam-beam interactions unambiguously.

In a short test run, T_1 was also used in order to extend the rapidity coverage of the double arm trigger to the interval $2.5 < |\eta| < 5.6$. The additional contribution of this more inclusive trigger was found to be negligible within the limitation of present statistical uncertainties.

The different contributions to the total inelastic rate are listed in table 1, where the quoted errors are statistical. The majority of the events have tracks in both arms and trigger the left-right coincidence. About 20% of the events have tracks on one side only and are recorded by the single-arm trigger.

The fraction of events escaping detection, due to the limited coverage in polar angle of the detectors, was estimated by extrapolation. For each event of the single-arm trigger, the tracks having the smallest and the largest production angle, $\theta_{\min}$ and $\theta_{\max}$, were considered. Extrapolation of the observed $\theta_{\max}$ distribution of event rate to the experimentally inaccessible region $0^\circ < \theta_{\max} \lesssim 0.5^\circ$ allows to estimate the number of events with all secondaries travelling inside the vacuum pipe. Similarly, the losses at large angles were estimated by extrapolation of the $\theta_{\min}$ distribution. As shown in table 1, the losses are estimated to amount to no more than $\sim 2\%$ of the total inelastic rate. This can be understood by noting that, while the angular range covered in this experiment is relatively small, the corresponding η -range is large. It is in fact the same as for a 4π angular coverage at an energy $\sqrt{s} \approx 20$ GeV. Moreover, the density of secondaries per unit rapidity range increases with energy.

TABLE 1

	η -range	Number of events	Fraction of the total
Left-right trigger	$3.0 < \eta < 5.6$	4996 ± 71	78.2%
Single arm trigger	$3.0 < \eta < 5.6$	$(2 \times 639) \pm 110$	20.0%
Extrapolation to small angles	$ \eta > 5.6$	45 ± 10	0.7%
Extrapolation to large angles	$ \eta < 3.0$	55 ± 25	0.9%
Correction for random incoming beam		15 ± 10	0.2%
Total		6389 ± 134	100%

From the corrected number of events given in table 1, the average rate of inelastic interactions per bunch crossing was found to be $N_{\text{in}} = (9.90 \pm 0.21) \times 10^{-5}$ events/crossing. In addition to the $\sim 2\%$ statistical error, the inelastic rate is affected by a systematic error of $\sim 2\%$ mainly due to uncertainties in the extrapolation procedure and inefficiency of the trigger and of vertex finding for very low multiplicity events.

The total number of elastic events was calculated from the observed number of events in the interval $0.05 < -t < 0.19 \text{ GeV}^2$ under the assumption of an exponential t distribution with a constant slope parameter $b = 17.2 \text{ GeV}^{-2}$, equal to the value measured [1] in the accessed t -range. In that case $(dN_{el}/dt)_{t=0} = b N_{el}$. The average rate of elastic events, after correction for acceptance, for chamber and track finding inefficiencies and for particle loss due to nuclear absorption was $N_{el} = (2.43 \pm 0.12) \times 10^{-5} \text{ events/crossing}$.

By substitution of the observed rates into eq. (1), one obtains $\sigma_{tot} = 66 \pm 7 \text{ mb}$ for $\rho = 0$. The quoted error is purely statistical and is mainly due to the uncertainty in the extrapolation to the optical point. The systematic error due to setting the factor $(1 + \rho^2)$ equal to unity is expected to be small compared to the statistical error; the dispersion relation fit of ref. [4] predicts a value of ρ of about 0.1 at Collider energies. An estimate of the systematic uncertainty arising from the possibility that for $-t < 0.05 \text{ GeV}^2$ the slope parameter b differs from the value in the covered t -range can be given by mentioning that a change of 1 GeV^{-2} in the value of the slope parameter at $-t = 0.05 \text{ GeV}^2$ would lead to a change in the total cross section of about 3 mb. The same change would result from a 5% error in the inelastic rate.

The simple "geometrical scaling" model predicts that the ratios σ_{el}/σ_{tot} and b/σ_{tot} do not vary with energy. Our results are $\sigma_{el}/\sigma_{tot} = 0.20$ and $b/\sigma_{tot} = 0.26 \text{ GeV}^{-2}/\text{mb}$ with an overall error of about 10%. It should be noted that because of the assumption of a constant slope parameter, the two ratios are not independent. For proton-proton interactions, over the ISR energy range, σ_{el}/σ_{tot} and b/σ_{tot} are almost constant and take the values 0.18 and $0.30 \text{ GeV}^{-2}/\text{mb}$, respectively [5]. The proton-antiproton results [6] at $\sqrt{s} = 53 \text{ GeV}$ are consistent with the pp data.

The value of the proton-antiproton total cross section at $\sqrt{s} = 540 \text{ GeV}$ is plotted in fig. 3 together with pp and $p\bar{p}$ results at lower energies. The full line in fig. 3 is the result of a dispersion relation fit [4] of data on σ_{tot} and ρ up to ISR energies (but not including the recent ISR $p\bar{p}$ measurement of ref. [6]); the dashed lines

indicate the uncertainty of the fit itself. Cosmic ray data were reported [7] in this energy region. They are affected by serious systematic uncertainties. However, under a certain choice [8] of the primary radiation spectrum, the data of ref. [7] interpolate fairly well between the ISR and Collider data points.

Our result indicates that the $p\bar{p}$ total cross section continues to rise strongly from the ISR to the Collider energy range. The experimental value of 66 ± 7 mb agrees well with the fit of ref. [4], which follows a $(\log s)^2$ dependence, but due to the sizeable uncertainty limits our result is also compatible with a slower increase with energy.

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FIGURE CAPTIONS

- Fig. 1 Layout of one arm of the inelastic detector; the assembly is symmetric with respect to the crossing region. The central detector of experiment UA2 placed in the same intersection region is also sketched. The η acceptance of the trigger planes T_1 , T_2 and T_3 is indicated.
- Fig. 2 Transverse (x , y) and longitudinal (z) distributions of reconstructed vertices.
- Fig. 3 Total cross section data for proton-proton (open points) and proton-antiproton (full points) interactions. To the compilation of ref. [4] the more recent results for $p\bar{p}$ at the ISR [6] and for pp and $p\bar{p}$ at FNAL [9] were added. The lines represent the dispersion relation fit of ref. [4].

UA4
inelastic detector

Fig. 1

Fig. 2

Fig. 3