EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 84-91
25 July 1984

MEASUREMENT OF THE PROTON-ANTIPROTON TOTAL AND ELASTIC

CROSS SECTIONS AT THE CERN SPS COLLIDER

UA4 Collaboration
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ABSTRACT

The proton-antiproton total cross section was measured at the c.m. energy $\sqrt{s} = 546$ GeV. The result is $\sigma_{\text{tot}} = 61.9 \pm 1.5$ mb. The ratio of the elastic to the total cross section is $\sigma_{\text{el}}/\sigma_{\text{tot}} = 0.215 \pm 0.005$. A comparison to the lower energy data shows that the increase of the total cross section with energy is very close to a $\log^2(s)$ behaviour.

Submitted to Physics Letters B

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EP/2113P/MH/ef

The proton-antiproton total cross section σ_{tot} was measured at the CERN SPS Collider ($\sqrt{s} = 546$ GeV) by means of a method already used in an earlier experiment [1] which is based on the simultaneous measurement of small-angle elastic scattering and of the total inelastic rate. Through the optical theorem, the total cross section can be expressed in terms of the forward differential elastic rate as

$$\sigma_{\text{tot}}^2 = \frac{1}{L} \cdot \frac{16\pi (Mc)^2}{1 + \rho^2} \cdot \left. \frac{dN_{\text{el}}}{dt} \right|_{t=0} \quad (1)$$

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,

$$\sigma_{\text{tot}} = (N_{\text{el}} + N_{\text{inel}})/L ,$$

where N_{el} and N_{inel} are the elastic and inelastic rates respectively. Combining the two expressions one can eliminate the luminosity L and obtain

$$\sigma_{\text{tot}} = \frac{16\pi (Mc)^2}{1 + \rho^2} \cdot \frac{dN_{\text{el}}/dt|_{t=0}}{N_{\text{el}} + N_{\text{inel}}} \quad (2)$$

In this Letter we present a result obtained by use of eq. (2), which allows a luminosity independent determination of the total cross section. As a consistency check, a less accurate value of σ_{tot} was also derived from eq. (1), using the measurement of machine luminosity as obtained from the determination of the beam profile.

The data for the total cross section measurement were mainly collected in a dedicated high- β run with machine optics especially designed to detect low- t elastic scattering. It was ensured that the N_{el} and the N_{inel} were measured at the same luminosity by simultaneously enabling both triggers, the inelastic trigger being suitably prescaled.

Details on the elastic scattering measurements are given in the accompanying Letter [2]. The apparatus to measure the inelastic rate [3] is shown in fig. 1. Two identical systems of three telescopes (D_1 , D_2 , D_3) placed symmetrically on the left and right sides of the crossing region cover polar angles from 0.4° up to 10° , corresponding to the pseudo-rapidity range $2.5 < |\eta| < 5.6$. Each telescope is composed of six drift chamber planes [4] followed by a plane of trigger counters (T_1 , T_2 and T_3

respectively). The coordinate along the drift wire is measured by means of a delay line close to the drift wire itself, which provides an unambiguous reconstruction of space points. The track finding procedure is therefore greatly simplified. Moreover, the readout of the delay line at both ends provides a constraint that facilitates the handling of multiple hits.

The region of polar angles $\theta > 20^\circ$ ($|\eta| < 1.7$) is covered by the central detector (CD) of the UA2 Collaboration [5] that was also used in the data taking. All detectors have full azimuthal acceptance and together they provide complete solid angle coverage around the crossing region, with the exception of a small gap for θ between 10° and 20° and of the forward region, $\theta < 0.4^\circ$, which is made inaccessible by the presence of the vacuum pipe.

Two symmetrical telescopes of three scintillation counters each, placed at a distance of ~ 11 m from the crossing point on both sides, viewed the interaction region at an angle of $\sim 5.1^\circ$. The left-right coincidence of these counters is affected by negligible background ($< 0.1\%$) and provides a luminosity monitor which detects $\sim 5.7\%$ of the total inelastic rate.

The measurement of the inelastic rate requires a trigger as inclusive as possible and a clear discrimination of beam-beam events from background interactions.

The following triggers were used:

- (a) A double-arm trigger $[(T_2 + T_3)_{\text{left}} * (T_2 + T_3)_{\text{right}}]$ covering the range $3.0 < |\eta| < 5.6$ on each side, which detects the near totality of non-diffractive events;
- (b) A single-arm trigger $[(T_1 + T_2 + T_3)_{\text{left}} * (T_2 + T_3)_{\text{right}}]$, covering the range $2.5 < \eta < 5.6$ on the outgoing p side. It detects events escaping the double-arm trigger, mostly diffractive interactions with all visible tracks in one arm only;

- (c) A central-detector trigger $[CD \times (T_2 + T_3)_{\text{left+right}}]$ which detects events with charged tracks at large angles only, in the range $-1.7 < \eta < 1.7$.

The data with the single arm and the central detector triggers were mainly taken during the usual low- β high luminosity runs because of the much more favourable signal to background ratio. The data were then normalized using the luminosity monitor.

In order to discriminate beam-beam interactions from background, a first selection is made by rejecting those events in which the time-of-flight analysis shows a hit of a trigger counter by a halo particle in time with the incoming beams ("in"). This selection removes $\sim 50\%$ of the triggers of the high- β runs (a few percent only in low- β), but also causes a small loss of good beam-beam events. This loss was monitored all over the data taking by looking at the time-of-flight configuration in the elastic events: the probability of a random "in" was thus measured to be 0.4%. In the surviving triggers, beam-beam interactions are recognized by reconstructing a vertex from the observed tracks.

Tracks are reconstructed by demanding track points in at least four out of the six drift chamber planes in any telescope. This requirement ensures full detection efficiency for charged particles over the entire solid angle covered by the apparatus. The errors on the space points were evaluated from the distributions of the fit residuals. The r.m.s. values for the drift and the delay line coordinate were found to be 0.34 mm and 2.1 mm respectively under actual running conditions, including all uncertainties in calibrations and geometrical survey. The accuracy of the delay line measurement provides the required resolution on the vertex reconstruction, which does not need to be better than the size of the interaction region, and is fully adequate for a powerful pattern recognition analysis.

The search for an interaction vertex is performed by means of a clustering algorithm based on the full covariance matrix computed for each fitted track. The transverse distribution of the reconstructed vertices

is plotted in fig. 2(a). Its width (~ 7 mm), although larger than the transverse beam dimensions, allows the rejection of all beam pipe interactions. In order to make use of all available information, the additional requirement that the vertex lie on the beam axis was included in the vertex finding algorithm. This is essential in the analysis of single-arm triggers since it allows to retain beam-beam events with only one charged track above the minimum detectable angle. In fact, events with this topology are known to constitute a non-negligible fraction of the diffractive dissociation component.

The vertex coordinate along the beam axis is determined by standard χ^2 minimization, retaining as vertex associated tracks only those that contribute an amount smaller than three standard deviations to the total χ^2 of the vertex. The longitudinal distributions of the reconstructed vertices for both double and single-arm triggers are shown in fig. 2(b) and (c) respectively. For comparison, the dotted histogram in fig. 2(b) shows the distribution of interaction vertices in the sub-sample of events observed by the UA2 central detector at larger angles: the slightly larger size of the interaction region is accounted for by the bigger error of the reconstructed z-coordinate of the vertex. The tails in fig. 2(c) are larger than in fig. 2(b) because of the lower multiplicity and the smaller average angles of tracks in single-arm events.

The individual contributions of the various triggers to the total inelastic rate are listed in table 1, together with the extrapolations to full angular coverage. The quoted errors contain both the statistical and systematic uncertainties; the latter dominate.

TABLE 1

Trigger contribution or correction	η -range	Fraction of N_{inel} (%)
Double-arm	$3.0 < \eta < 5.6$	82.7 ± 0.8
Single-arm	$2.5 < \eta < 5.6$	16.3 ± 0.6
Central detector	$ \eta < 1.7$	0.08 ± 0.04
small-angle extrapolation	$ \eta > 5.6$	0.9 ± 0.2
large-angle extrapolation	$1.7 < \eta < 2.5$	0.04 ± 0.02

The single-arm rate was mostly studied by triggering on the outgoing antiproton side because it was less affected by background. The observed rate was then multiplied by two. A cross-check on a sample of proton-side triggers gave consistent results.

The single-arm contribution includes a correction, amounting to 0.9% of the total inelastic rate, to account for losses of low-multiplicity events due to the dead area of chamber frames. This loss was evaluated by a Monte-Carlo calculation using as input the observed angular distribution of tracks. A small beam gas background (0.4%) compatible with the measured residual pressure, has been subtracted from the observed single-arm rate.

To obtain the total inelastic rate, the fraction of events escaping detection due to the incomplete angular coverage was estimated by extrapolation. No correction has to be applied to the detected rate of double-arm interactions since events escaping the left-right coincidence are rescued by the single-arm trigger. For each event of the single-arm trigger, the track with the largest production angle $\theta_{\max}$ is considered. The $dN/d\cos\theta_{\max}$ distribution of the events is shown in fig. 3(a) against the variable $\theta_{\max}$, together with an empirical curve fitting the data. The extrapolation to $\theta_{\max} = 0$ represents a model independent procedure to estimate the loss at small angles, which was found to be 5.3% of the single arm, i.e. 0.9% of the total inelastic rate.

In order to evaluate the losses in the uncovered region between telescope D_1 and the UA2 central detector ($1.7 < |\eta| < 2.5$), the smallest production angle $\theta_{\min}$ is considered for each event of the single-arm trigger in which no tracks are present in the central detector. An empirical extrapolation of the $\eta_{\max}$ distribution (equivalent to $\theta_{\min}$), shown in fig. 3(b), leads to a correction of the total inelastic rate of $(0.04 \pm 0.02)\%$.

A source of systematic error in the method used for the small angle extrapolation might arise from events with a very forward topology, such as a possible N^* production. However, a Monte-Carlo simulation allows to estimate that about one third of the N^* two-body decays would fall inside the acceptance of the apparatus. One can therefore include this

effect in the extrapolation procedure by assuming that two components are present in the maximum angle distribution of fig. 3(a): a single exponential in $\theta_{\max}$, together with the more forward peaked N^* decays from the Monte-Carlo generation. The relative size of these two components is then left as a free parameter in the fit. In this hypothesis an upper limit to the small angle losses can be set, which would change the entry in table 1 to $(0.9 \pm 0.2)^{\circ.9}\%$. Taking into account all sources of errors, the overall uncertainty on the total inelastic rate is evaluated as 1.3%, the statistical error contributing by 0.5%.

To obtain the optical point, the differential elastic rate has been extrapolated using the small angle data only ($-t < .15 \text{ GeV}^2$) and "linear" fits $\exp(bt)$ which give good description of these data [2]. The value of the extrapolated forward rate is independent (within 0.3%) of the maximum t used in the fit (provided $|t|_{\max} < .15 \text{ GeV}^2$) and it is determined with a statistical error of 1%. "Quadratic" fits $\exp(Bt + Ct^2)$ have been tried in the same t range and, although giving a value of C consistent with zero, are in average 0.8% higher for the extrapolated forward rate than that determined by the "linear" fits. The contribution of the Coulomb interference term ($\sim 1.3\%$ at $-t = 0.03 \text{ GeV}^2$) was taken into account in these fits.

The calculation of the elastic rate requires an accurate calibration of the drift-timing and charge division coordinates of the wire chambers in the elastic scattering system. The drift and charge division parameters have been extensively studied [6] in a test beam. More importantly, the redundancy in the number of drift planes per detection telescope allowed a precise calibration of the drift coordinates from the data taken during the experiment itself. The charge division readout of the plane of proportional wires in each chamber was calibrated with respect to the hodoscope of scintillation counters [2] placed directly behind it, again with data from the elastic trigger itself. The resulting uncertainty on the calculated element of solid angle is less than 2%. The value of the overall uncertainty on the extrapolated rate per unit solid angle is then 2.5%. The same correlated error is attributed to the integrated rate

N_{el} .

Using eq. (2) and assuming $\rho = 0.15$ as suggested by the dispersion relation fit of ref. [7] we obtain for the total cross section the value $\sigma_{\text{tot}} = 61.9 \pm 1.5$ mb. An additional systematic error of 1% is due to the uncertainty of the beam momentum, that was measured^(*) to be 273 ± 1.4 GeV/c [8]. The ratio of the elastic to the total cross section is found to be $\sigma_{\text{el}}/\sigma_{\text{tot}} = 0.215 \pm 0.005$. The integrated elastic cross section is $\sigma_{\text{el}} = 13.3 \pm 0.4$ mb. Earlier results with low statistics [1,9] are compatible with the present measurement. Our results on σ_{tot} and the ratio $\sigma_{\text{el}}/\sigma_{\text{tot}}$ are shown in figs 4 and 5 respectively, together with $\bar{p}p$ and pp data at lower energies [10-13].

The total cross section was also derived according to eq. (1) from the measured elastic rate and the machine luminosity as obtained from the determination of the beam profile by the wire scan technique [14]. During the high- β run the luminosity monitor was calibrated several times with respect to the wire scan. The ratio of the monitor rate to the measured luminosity was constant within 3.2% (r.m.s. value). The integrated luminosity was obtained from the total monitor rate during data taking. The measurement of the luminosity has an estimated systematic error of 10%, which reflects in a 5% error on σ_{tot} ; the contribution of the error from the elastic rate is in this case negligible. We obtained the result $\sigma_{\text{tot}} = 61 \pm 3$ mb, which agrees with the more accurate value from the luminosity independent method.

Our measurement of the total cross section is in good agreement with the extrapolation of the dispersion relation fit of ref. [7]. We have performed a fit on the $\bar{p}p$ and pp total cross section data for $\sqrt{s} > 5$ GeV using the expression

$$\sigma_{\text{tot}} = \sigma_0 + C_1 E^{-\alpha_1} \pm C_2 E^{-\alpha_2} + \sigma_1 \log^Y(s) ,$$

where the upper and the lower sign refer to $\bar{p}p$ and pp respectively, and E is the incident laboratory energy [7]. The values of the seven parameters as determined by the fit are listed in table 2.

(*) This measurement indicates that the Collider was operated up to now at a beam momentum 1.1% higher than the nominal value (270 GeV/c). Therefore, the σ_{tot} value given in ref. [1] should be scaled down by 2.2%.

TABLE 2

σ_0	=	27.	$\pm$	1.6	mb
C_1	=	44.8	$\pm$	0.8	mb
C_2	=	24.9	$\pm$	1.2	mb
α_1	=	0.38	$\pm$	0.02	
α_2	=	0.56	$\pm$	0.01	
σ_1	=	0.25	$\pm$	0.06	mb
γ	=	1.9	$\pm$	0.1	

The results of the present experiment show that the increase of the total cross section from ISR to Collider energy is very close to a $\log^2(s)$ behaviour. The ratio σ_{el}/σ_{tot} is definitely larger at the Collider than at ISR energies, where it has a nearly constant [11] value of 0.175 ± 0.001 . This increase provides clear evidence for violation of geometrical scaling. It also is in disagreement with models based on the "critical Pomeron" concept, since in this class of models the ratio σ_{el}/σ_{tot} is predicted to decrease with energy. The rise of σ_{el}/σ_{tot} is in qualitative agreement with the notion - inherent to various optical models - that the nucleon opacity is still increasing and that, although the Froissart bound appears to be qualitatively saturated, the present energy is still far away from the asymptotic regime.

Acknowledgements

We are very grateful to our colleagues of the UA2 Collaboration who provided us with the information from the central detector. We wish to express our gratitude to the staff of the CERN Accelerator Divisions for the help in the installation and survey of this experiment, and for the successful operation of the SPS Collider during the dedicated high- β run when this measurement was performed. Special thanks go to P. Faugeras of the SPS Division who carefully designed the high- β optics. The continued effort of the technicians at CERN, INFN and NIKHEF who contributed to this experiment is warmly acknowledged.

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FIGURE CAPTION

Fig. 1 Layout of one arm of the inelastic apparatus (the full detector is symmetric with respect to the crossing region). The η -acceptance of the trigger planes T_1 , T_2 , T_3 and of the UA2 Central Detector is given. One arm of the monitor telescopes is also shown.

Fig. 2 (a) Transverse distribution of reconstructed vertices in double-arm events (the arrows indicate the position of the pipe wall);

 (b) longitudinal distribution of vertices in double-arm events; the dotted histogram is the distribution reconstructed by the UA2 central detector in the same sample of events;

 (c) longitudinal distribution of vertices observed in single-arm events.

Fig. 3 (a) $\theta_{\max}$ distribution of single-arm events for the evaluation of the loss at small angles;

 (b) $\eta_{\max}$ distribution of single-arm events for the evaluation of the loss in the gap between 10° and 20° .

Fig. 4 The result of the present experiment on the $\bar{p}p$ total cross sections at $\sqrt{s} = 546$ GeV is shown together with lower energy $\bar{p}p$ and pp data.

Fig. 5 The ratio σ_{el}/σ_{tot} from the present experiment is shown together with lower energy data.

Fig. 1

CD	η acceptance
T_1	$-1.7 \rightarrow 1.7$
T_2	$2.5 \rightarrow 3.5$
T_3	$3.0 \rightarrow 4.8$
	$4.4 \rightarrow 5.6$

UA2 Central Detector

Fig. 2

Fig. 3

Fig. 4

Fig. 5