Measurement of the $\bar{p}p$ Total Cross Section at $\sqrt{s}=1.8$ TeV

N. A. Amos,[3] C. Avila,[3] W. F. Baker,[3] M. Bertani,[1] M. M. Block,[6] D. A. Dimitroyannis,[5] D. P. Eartly,[3] R. W. Ellsworth,[4] G. Giacomelli,[1] B. Gomez,[3,a] J. A. Goodman,[5] C. M. Guss,[6] A. J. Lennox,[3] M. R. Mondardini,[1] J. P. Negret,[3,a] J. Orear,[2] S. M. Pruss,[3] R. Rubinstein,[3] S. Sadr,[6] S. Shukla,[2] I. Veronesi,[1] and S. Zucchelli[1]

[1]*Universitá di Bologna and Istituto Nazionale di Fisica Nucleare, Bologna, Italy*

[2]*Cornell University, Ithaca, New York 14853*

[3]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[4]*George Mason University, Fairfax, Virginia 22030*

[5]*University of Maryland, College Park, Maryland 20742*

[6]*Northwestern University, Evanston, Illinois 60201*

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We have measured the antiproton-proton total cross section at $\sqrt{s}=1.8$ TeV at the Fermilab Tevatron Collider; the value obtained is 78.3 ± 5.9 mb. B, the nuclear slope parameter for elastic scattering, was measured to be 16.3 ± 0.5 $(\text{GeV}/c)^{-2}$. From these data, we derive a value for the total elastic cross section.

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The $\bar{p}p$ total cross section, like all other measured hadron total cross sections, is observed[1-8] to fall with increasing energy, reach a minimum around $\sqrt{s}=20$ GeV, and then rise as the energy is further increased. At CERN ISR and SPS energies, the total cross-section energy increase could be fitted by $\log^2 s$, but it was not possible to tell whether the $\log^2 s$ dependence would continue to higher energies, or whether it might begin to approach some asymptotic value. We report here a measurement of the $\bar{p}p$ total cross section at $\sqrt{s}=1.8$ TeV, using the Fermilab Tevatron Collider, to study further the energy dependence of this quantity.

The experimental method is to measure $\bar{p}p$ nuclear elastic scattering at small values of $|t|$ (where t is the square of the four-momentum transfer), and extrapolate the data to $t=0$. Using the optical theorem, the following relations are obtained:

$$\left.\frac{dN}{dt}\right|_{t=0}=L,\quad \left.\frac{d\sigma}{dt}\right|_{t=0}=L\frac{(1+\rho^2)\sigma_T^2}{16\pi}, \tag{1}$$

where dN/dt is the differential number of events observed for an integrated luminosity L, $dN/dt|_{t=0}$ is its value extrapolated to $t=0$, ρ is the real-to-imaginary forward-scattering-amplitude ratio, and σ_T is the total cross section. Our experiment thus determines $(1+\rho^2)\sigma_T^2$; using extrapolations of lower-energy values of ρ, we can obtain σ_T.

We have already published[9] a value of B, the nuclear slope parameter, from the data taken at the Collider. The data reported here are from a later running period; many of the experimental details are identical for the two runs, and will not be reported here. However, several improvements giving rise to much improved stability and efficiency of the apparatus and data were made between the two runs both to our detectors and to the accelerator. Among the former were new, high-efficiency, trigger scintillation counters in the "Roman pots"; use of a scintillation counter in each pot with accurately machined holes in its face and accurately machined edges, in order to obtain continuous calibration of the drift-chamber readout; improvements in the drift-chamber readout electronics; and improvements in the composition stability of the drift-chamber gas mixture.

In the accelerator, there have been substantial increases in luminosity since the earlier running period, to over 10^{28} cm^{-2}sec^{-1} at our intersection region. Beam scrapers are now available in the Tevatron and were used to obtain the data reported here. They were used to remove beam halo and reduce the 95% normalized transverse emittance of the circulating beams from about 20π mm mr to under 5π mm mr in both the horizontal and vertical planes. This was achieved by scraping away up to $\sim80\%$ of the luminosity; further rescraping was carried out every few hours. The cleanliness of the beams allowed us to place our detectors with their closest edges only 2.2 mm from the center of the beams, corresponding to a minimum $|t|$ of 0.0007 $(\text{GeV}/c)^2$. Some accelerator injection magnets near our equipment, whose steel yokes had been only a few mm from the beams, were made remotely moveable for this run, giving a considerable reduction in background counting rates. For the data reported here, the accelerator was operated with a lattice of better known properties than for our earlier data; this lattice also gave a somewhat smaller beam divergence than previously at our interaction region. The accelerator β functions at this point were 72 and 73 m in the horizontal and vertical planes, respectively.

The detectors used were in the outer "Roman pots," shown in Fig. 1 of Ref. 9, located in the accelerator about 100 m on each side of the interaction point. The effective distances to these outer detectors [$\sim$80 m in the vertical (scattering) plane and $\sim$40 m in the horizontal plane] were obtained from the properties of the Tevatron lattice, using measured values of the magnetic fields of the Tevatron magnets.[10] We experimentally verified the vertical effective distances (to $\sim\pm 1\%$) during a special run in which elastic events were detected where the scattered particles passed through both the inner detectors (which were at a known distance) and the outer detectors. In the data reported here, our detectors covered the $|t|$ range $0.0007 < |t| < 0.1$ $(\text{GeV}/c)^2$; we present results using the range $0.02 < |t| < 0.08$ $(\text{GeV}/c)^2$. The lower-$|t|$-range data are still being analyzed.

Relative monitoring of the accelerator luminosity was by means of a ninefold coincidence of eight counters placed around the beam pipe (four each located on either side of the interaction point and 12 m from it covering the pseudorapidity range $6.0 < \eta < 6.5$), together with an accelerator signal indicating the time of beam collision. This monitor, after subtraction of a small ($\sim$1%) accidental background, was normalized to the absolute luminosity determined from accelerator data. The stability of the monitor to the accelerator luminosity was better than 5%. Proton and antiproton transverse intensity distributions in both planes were determined by flying thin wires through the beams at two locations in the accelerator and recording the resulting radiation in nearby detectors.[11] Using the known accelerator lattice, the transverse beam intensity distributions at our interaction point could be inferred. Beam intensities were determined using the sampled bunch display,[12] obtained from current pickups in the accelerator. Using all of this information, absolute luminosities at our interaction point were determined,[13,14] with a presently estimated accuracy of $\pm 15\%$; this uncertainty is the dominant one in our determination of the total cross section.

Event selection and data analysis were carried out in a modified version of that described in Ref. 9, which was based on the procedure of Refs. 4, 15, and 16. After elimination of events that scintillation counters indicated were inelastic (our inelastic counters covered the pseudorapidity range $4.2 < \eta < 6.5$), the drift chambers for remaining events had very few wire hits not associated with particle tracks. At least two wires (out of the four) with high efficiency were selected in each chamber; events were retained with the requirement of a single hit in at least two wires of those selected, with the vertical coordinates of hits in the wires required to be within 500 μm of each other. Measured chamber efficiencies for recording elastic events were always over 90%, and were typically about 96%. Extensive studies showed that there was negligible background in the elastic data in the fiducial-chamber area used in the analysis when the above selection criteria were used, and the loss of good events was also negligible. Out of 400 000 recorded events, we obtained 200 000 elastic events, which were reduced by fiducial cuts on detector area for this analysis to a 50 000 final event sample.

The cross section $d\sigma/dt$ consists of three terms: Coulomb, Coulomb-nuclear interference, and nuclear scattering. The Coulomb effects are small in the range of t discussed here, although they have been included in the analysis.

We have analyzed data from a total of seven runs, each lasting about 2 h, taken in two periods separated by about a month. Detector position (and thus binning in t) were not always the same for each run. Figure 1 shows data from one of the runs with 5000 elastic events. Using Eq. (1) and the following form for nuclear scattering,

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp(-B|t|) , \qquad (2)$$

we obtain, for the data of Fig. 1, values of $\sigma_T(1+\rho^2)^{1/2} = 79.7 \pm 1.7$ mb, and $B = 16.0 \pm 0.9$ $(\text{GeV}/c)^{-2}$ with a χ^2 per degree of freedom of 0.82; these errors are statistical. After combining all runs and adding quadratically our estimates of systematic uncertainties (which include uncertainties in calibration of the chamber coordinates, uncertainties in the effective distances to the chambers, but not the uncertainty in luminosity), we obtain $\sigma_T(1+\rho^2)^{1/2} = 79.1 \pm 0.7$ mb, and our final value for $B = 16.3 \pm 0.5$ $(\text{GeV}/c)^{-2}$; note that this value of B is consistent with our earlier value[9] and supercedes it. After adding in the dominant $\pm 15\%$ uncertainty in luminosity, we obtain our final result for $\sigma_T(1+\rho^2)^{1/2}$ of 79.1 ± 6.0 mb. There is as yet no mea-

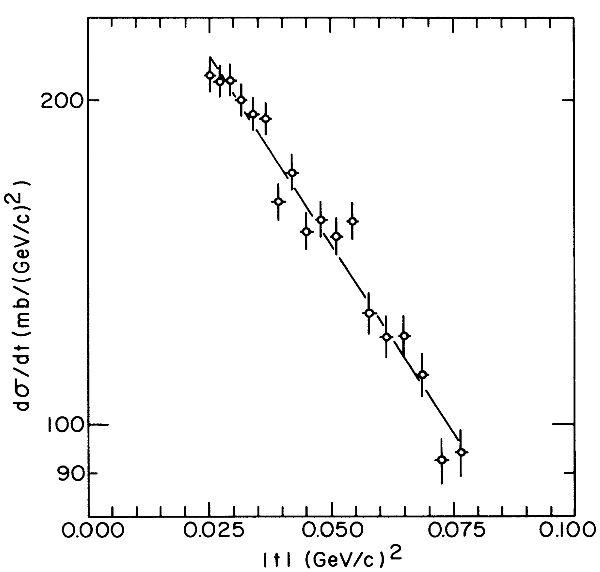

FIG. 1. Elastic-scattering distribution obtained from one run. The line shown is the fit discussed in the text.

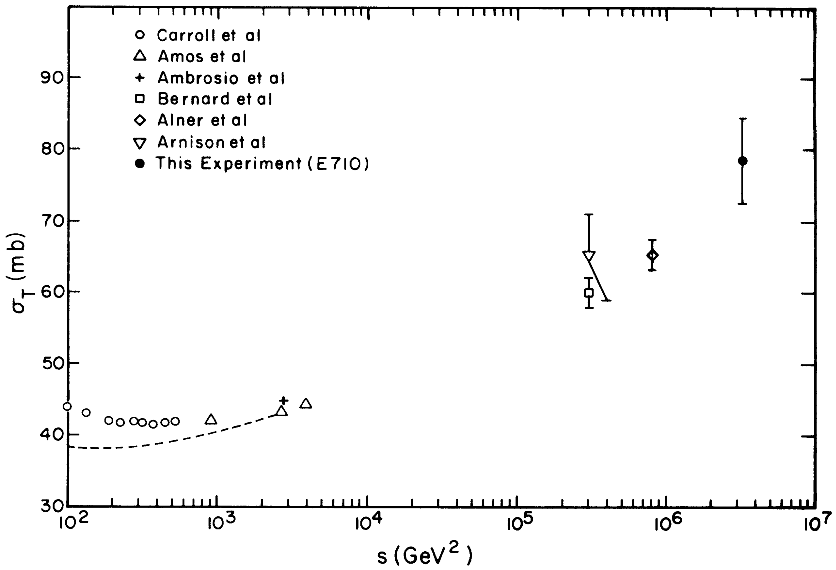

FIG. 2. The value of σ_T obtained from this experiment (using $\rho = 0.145$), together with previous $\bar{p}p$ data (Refs. 3-6, 8, and 18). The dashed curve shows the behavior of the $\bar{p}p$ total cross section.

surement of ρ at our energy. Using a value of 0.145, based on a fit to most lower-energy data,[17] we obtain $\sigma_T = 78.3 \pm 5.9$; using a value of 0.24, as obtained by UA4 (Ref. 18) at $\sqrt{s} = 546$ GeV, would reduce our value of σ_T by 1.8%.

We can measure a value for the total elastic cross section σ_{el} by integrating the elastic distribution, using the assumption that B is constant at all t. We obtain $\sigma_{el} = 19.6 \pm 3.0$ mb, and a ratio σ_{el}/σ_T of 0.25 ± 0.02.

Our value for σ_T fits well on an extrapolation from lower-energy data (see Fig. 2), as do our results for B, σ_{el}, and σ_{el}/σ_T. The data are consistent with a $\log^2 s$ increase of σ_T and do not appear to support σ_T eventually approaching a constant value at high energies. However, this point will be addressed more thoroughly after evaluation of data on ρ and σ_T which we have taken at several energies below $\sqrt{s} = 1.8$ TeV.

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[a]Present address: Departamento de Fisica, Universidad de los Andes, Bogota, Colombia.

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