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

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# MEASUREMENT OF THE $\bar{p}p$ TOTAL CROSS SECTION

AT  $\sqrt{s} = 1.8$  TeV

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## ABSTRACT

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

The  $\bar{p}p$  total cross section, like all other measured hadron total cross sections, is observed<sup>(1-8)</sup> to fall with increasing energy, reach a minimum around  $\sqrt{s} = 20$  GeV, and then rise as the energy is further increased. At the CERN ISR and SPS energies, the total cross section energy dependence could be fit 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:

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

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

We have already published<sup>(9)</sup> a value of  $B$ , the nuclear slope parameter, from the data taken during the first (1987) run of the Collider. The data reported here are from the 1988/1989 run; many of the experimental details are identical for the two runs, and will not be repeated here. However, several improvements 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 1987 run, to over  $10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$  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  $20\pi \text{ mm.mr}$  to under  $5\pi \text{ mm.mr}$  in both the horizontal and vertical planes. This was achieved by scraping away up to  $\sim 80\%$  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 detectors used were in the outer "Roman Pots", shown in Figure 1 of Reference 9, located in the accelerator about 100 meters on each side of the interaction point. The effective distances to these outer detectors ( $\sim 80$  meters in the vertical (scattering) plane and  $\sim 40$  meters in the horizontal plane) were obtained from the properties of the Tevatron lattice, using measured values of the magnetic fields of the Tevatron magnets<sup>(10)</sup>. 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  $0.025 < |t| < 0.08 \text{ (GeV/c)}^2$ . The lower  $|t|$  range data are still being analyzed.

Relative monitoring of the accelerator luminosity was by means of a 9-fold coincidence of 8 counters placed around the beam pipe (4 each located on either side of the interaction point and 12 meters from it), together with an accelerator signal indicating the time of beam collision. This monitor, after subtraction of a small accidental background, was normalized to the absolute luminosity determined from accelerator data. 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.<sup>(11)</sup> 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<sup>(12)</sup>, obtained from current pickups in the accelerator. Using all of this information, absolute luminosities at our interaction point were determined,<sup>(13,14)</sup> 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 Reference 9, which was based on the procedure of References 4, 15, and 16. After elimination of events that scintillation counters indicated were inelastic, 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  $500 \mu\text{m}$  of each other. Extensive studies showed that there was negligible background in the elastic data when these

selection criteria were used, and the loss of good events was also negligible.

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 7 runs, each lasting about two hours, taken in two periods separated by about a month. Figure 1 shows data from one of the runs with 5000 elastic events. Using equation (1) and the following form for nuclear scattering:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt} \bigg|_{t=0} \exp(-B|t|) \quad (2)$$

we obtain, for the data of Figure 1, values of  $\sigma_T(1+\rho^2)^{1/2} = 79.7 \pm 1.7$  mb, and  $B = 16.0 \pm 0.9$  (GeV/c)<sup>-2</sup>, with a  $\chi^2$  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, and the dominant  $\pm 15\%$  uncertainty in luminosity), our final results are  $\sigma_T(1+\rho^2)^{1/2} = 79.1 \pm 6.0$  mb, and  $B = 16.3 \pm 0.5$  (GeV/c)<sup>-2</sup>; note that this value of  $B$  is consistent with our earlier value<sup>(9)</sup> and supercedes it. There is as yet no measurement of  $\rho$  at our energy. Using a value of 0.145, based on a fit to most lower energy data<sup>(17)</sup>, we obtain  $\sigma_T = 78.3 \pm 5.9$ ; using a value of 0.24, as obtained by UA4<sup>(18)</sup> at  $\sqrt{s} = 546$  GeV, would reduce our value of  $\sigma_T$  by 2%.

We can measure a value for the total elastic cross section  $\sigma_{el}$  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  $\sigma_{el}/\sigma_T$  of  $0.25 \pm 0.02$ .

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

We wish to thank the Fermilab Accelerator Division for their help in making this measurement successful. We are particularly grateful to D. Finley, N. Gelfand, R. Johnson and S. Hsueh for their assistance in understanding the collider luminosity. A. Donati, R. DeSalvo, R. Maleyran, A. Manarin and G. Yodh were very helpful in the early stages of the experiment. This work was supported by the U.S. Department of Energy, the U.S. National Science Foundation, the Italian Ministero Pubblica Istruzione and the North Atlantic Treaty Organization.

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Figure Captions

*Figure 1: Elastic scattering distribution obtained from one run. The line shown is the fit discussed in the text.*

*Figure 2: The value of  $\sigma_T$  obtained from this experiment, together with previous pp data (References 3-6,8,18). The dashed curve shows the behavior of the pp total cross section.*

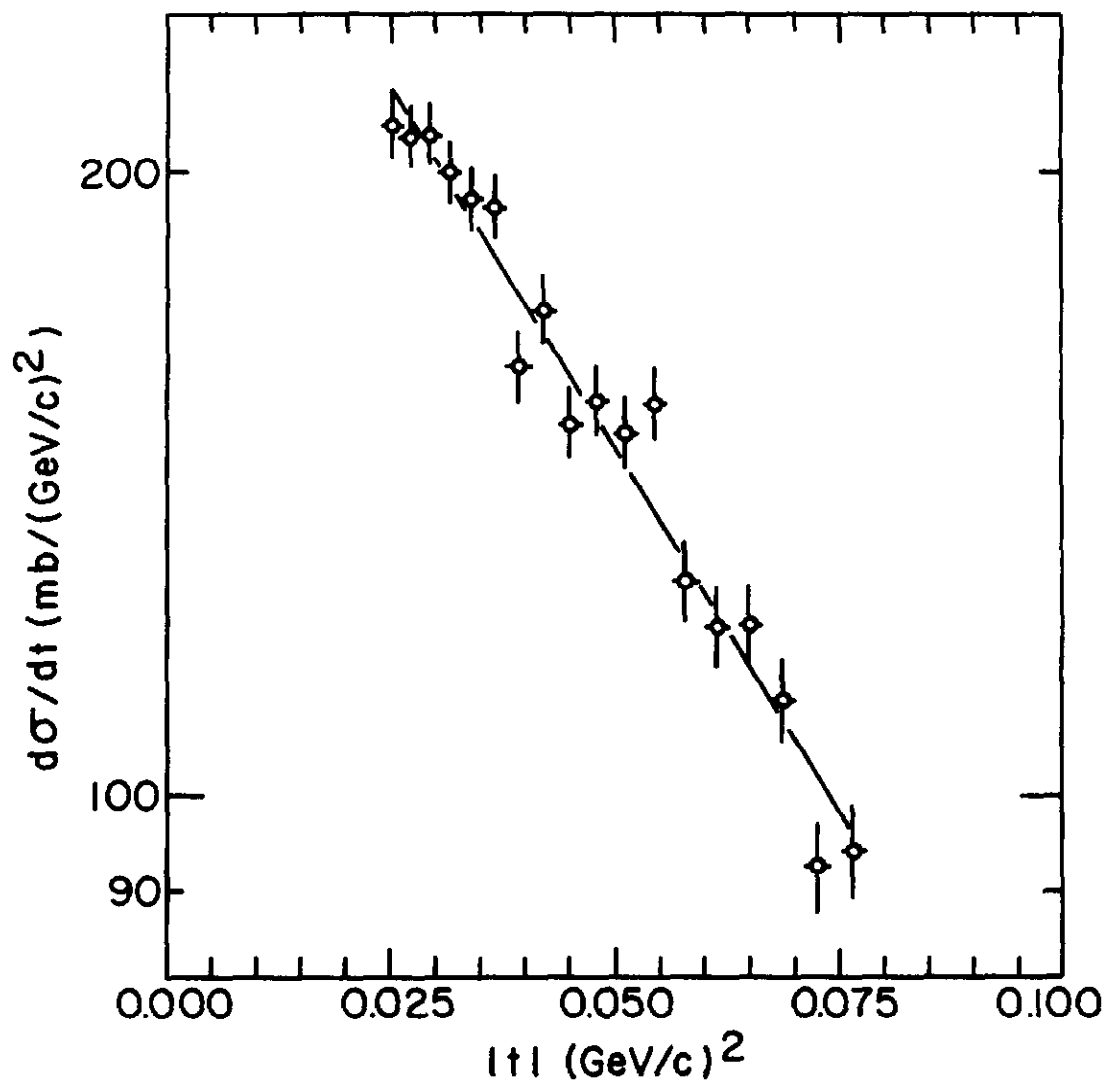


Figure 1

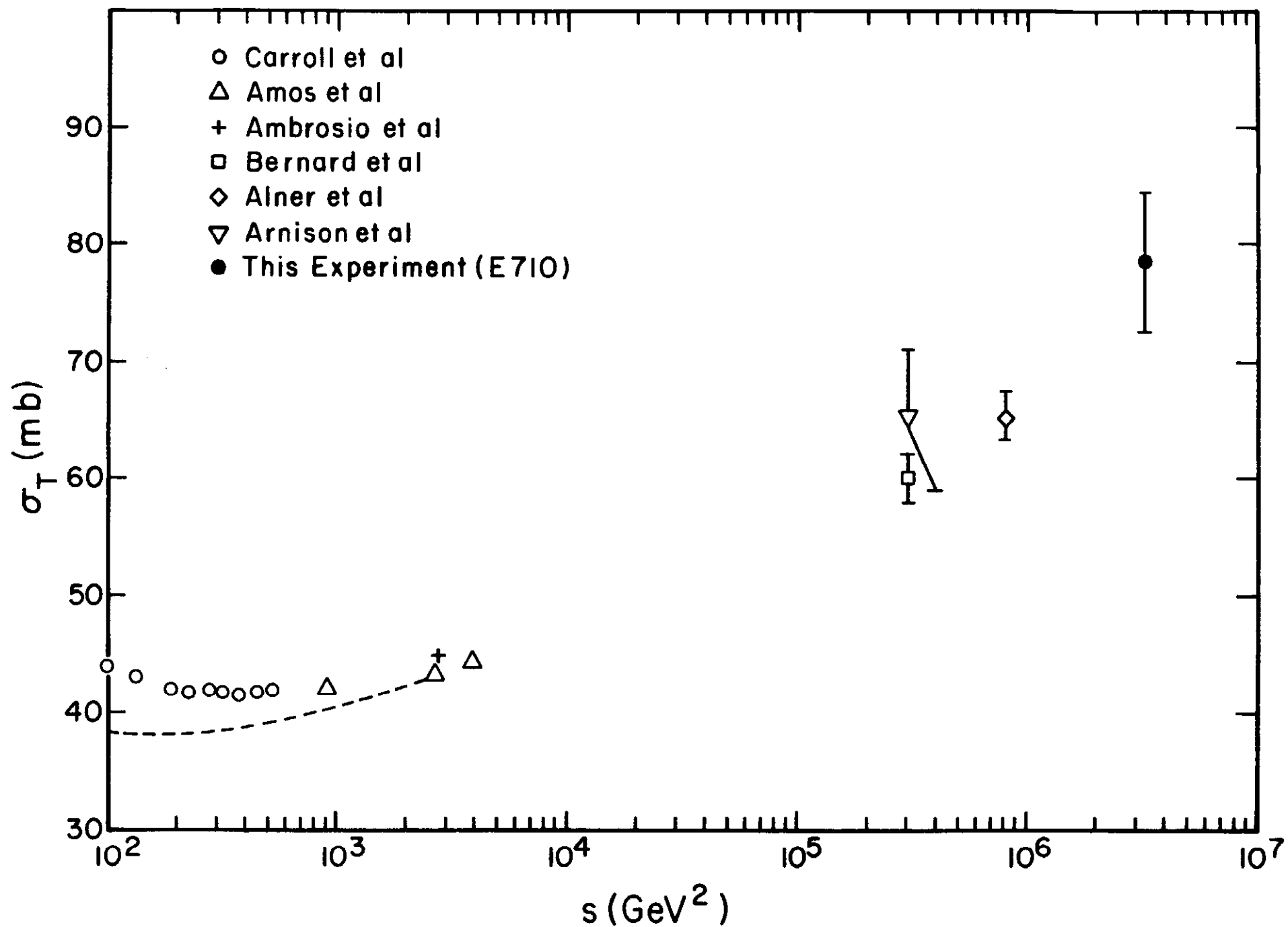


Figure 2