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A Measurement of the Proton-Antiproton Total Cross Section at $\sqrt{s} = 1.8$ TeV

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Abstract

We report a measurement of the $p\bar{p}$ total cross section at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron Collider, using the luminosity independent method. Our result is $\sigma_T = 71.71 \pm 2.02$ mb. We also obtained values of the total elastic and total inelastic cross sections.

At energies above $\sqrt{s} \sim 20$ GeV, the $p\bar{p}$ total cross section σ_T increases with increasing energy(1-8) (similar to all other measured hadron-hadron total cross sections). Accurate measurements of σ_T (together with those of ρ, the ratio of the real to imaginary part of the forward scattering amplitude) at the highest available energy should give information on how fast this increase is with energy, and whether or not the rate of increase is leveling off so that σ_T may approach a constant value at even higher energies. So far, there have been two previous measurements of σ_T at the Fermilab Tevatron Collider at the currently highest available energy of $\sqrt{s} = 1.8$ TeV, differing by some 2 standard deviations; E-710 has reported(9) 72.8 ± 3.1 mb and CDF has reported(10) 80.03 ± 2.24 mb. The aim of the present experiment, Fermilab E-811, is to measure this quantity to higher accuracy than previously; it has many features in common with our earlier E-710 experiment. The experiment was also designed to measure ρ; that analysis is still in progress.

We use the luminosity independent method to obtain σ_T, as in Refs. 7 and 9. Using the optical theorem, the total cross section can be expressed in terms of the forward differential number of nuclear elastic events

$$\sigma_T^2 = \frac{1}{L}\ \frac{16\pi(\hbar c)^2}{1+\rho^2}\ \frac{dN_{el}}{dt}\Big|_{t=0} \tag{1}$$

where L is the integrated luminosity. Another expression for the total cross section is

$$\sigma_T = \frac{1}{L}\ (N_{el} + N_{inel}), \tag{2}$$

where N_{el} and N_{inel} are the total elastic and total inelastic number of events respectively. By combining eqs. (1) and (2), we obtain

$$\sigma_T = \frac{16\pi(\hbar c)^2}{1+\rho^2}\ \frac{dN_{el}}{dt}\Big|_{t=0}\ \frac{1}{N_{el}+N_{inel}} \tag{3}$$

In equation (3), σ_T is determined independently of luminosity, which often has a large uncertainty. We measure N_{el} and N_{inel} simultaneously; the previously measured nuclear elastic distribution

$$\frac{dN_{el}}{dt} = \frac{dN_{el}}{dt}\Big|_{t=0}\ \exp(-B|t|)$$

with B = 16.98 ± 0.22, the mean from Refs. 9 and 11, is used to extrapolate our elastic data to t = 0. (Our data are consistent with this distribution, but with a larger uncertainty in the value of B because of the limited t range of this experiment.) N_{el} is obtained by integrating the fit to our elastic data from t = 0 to $t = -\infty$, using the above value of B.

The elastic detectors in this experiment were placed at the same Tevatron locations as those used for the lowest |t| measurements of E-710(9,12,13), and the accelerator magnetic lattice in the region of the experiment was unchanged between the two experiments. However, to detect the elastic events, this experiment used scintillating fiber high resolution detectors inside the Tevatron beam vacuum pipe. Each detector was a bundle of 15,000 scintillating fibers each of 100μ diameter, 4.5 cm long parallel to the Tevatron circulating proton and antiproton beams, and the detectors were moved until the closest fibers were only ~ 2mm from the center of the beams. The light from the fibers was transmitted by a glass fiber rod to two planar-focused image intensifiers in cascade, followed by a specially designed CCD, which was read out following a trigger from scintillation counters in line with the scintillating fiber bundles. The CCD signals were digitized and compressed using VDAS (Video Data Acquisition System) modules.(14) The particle resolution obtained in the detectors was measured to be ±38μm. Measured detector efficiencies were always greater than 0.97, as were the measured trigger scintillator efficiencies. Descriptions of the detectors are given in Refs. 15 and 16. There were two detectors at each location, one above the circulating beam and one below. Elastic events required a particle in the upper detector on the scattered proton side in coincidence with one in the lower detector on the scattered antiproton side, or vice versa; the timing of the particles was required to be consistent with them coming from a collision at the interaction point.

In the analysis stage, colinearity of the two scattered particles in both the horizontal and vertical planes was required. For the results reported here, data were analyzed over the range $0.0045 \lesssim |t| \lesssim 0.036$ $(\mathrm{GeV}/c)^2$; backgrounds varied from 20% in the bin closest to the beam to 1% at the farthest bin. The background, mainly due to a beam halo particle in the antiproton detector in accidental coincidence with a beam halo particle in the proton detector, was experimentally determined by 3 different methods, which gave consistent results. Two of the methods obtain the background from the shape of the distributions of non-colinear events in a pair of detectors, while the third used events from "upper-upper" or "lower-lower" detector pair combinations.

In order to obtain the nuclear elastic scattering, we subtract from the observed elastic distribution the distributions from Coulomb and Coulomb-nuclear interference. At our lowest $|t|$ bin, this was a 2.6% correction and rapidly became smaller for larger $|t|$ bins. We used a value for ρ of 0.145(17) in this correction.

The inelastic rate, N_{inel}, was obtained using an annular scintillation counter system and method essentially identical to that of E-710 (see Ref. 13 and its Figure 1). Coincidences (LR) of any one of 3 sets of annular counters on the left (L) and any one of 3 sets of counters on the right (R) of the interaction point, covering $5.2 < |\eta| < 6.5$, were made. The time of flight registered by the counters was required to be consistent with particles from the interaction point, and pulse heights were required to be at least as large as those from minimum ionizing particles. Background (~1%) due to accidental coincidences was subtracted.

We use the same method as that in E-710(13), which is similar in principle to that of UA4(7), to obtain those inelastic events not observed by the LR coincidences; the method has few assumptions, and almost all quantities are measured in this experiment. To the LR events $[(13503 \pm 64) \times 10^2]$ we added the single arm L and R events (0.322 ± 0.042 of the LR rate), and a small extrapolation (0.011 ± 0.006 of the LR rate) to account for those single arm events not observed because of the limited η coverage of the counters; this gives $N_{inel} = (17995 \pm 572) \times 10^2$ events. From our measured 28,000 elastic events, we obtain $N_{el} = (5081 \pm 35) \times 10^2$ events and $\frac{dN_{el}}{dt}\big|_{t=0} = (86282 \pm 603) \times 10^2\,(\mathrm{GeV}/c)^{-2}$. Our final result, obtained by averaging the values from our 10 runs, and assuming a ρ value of 0.145(17), is

$$\sigma_T = 71.71 \pm 2.02 \text{ mb}$$

where the error is predominantly statistical. We also obtain $\sigma_{el} = 15.79 \pm 0.87$ mb and $\sigma_{inel} = 55.92 \pm 1.19$ mb, and $\sigma_{el}/\sigma_T = 0.2202 \pm 0.0078$.

As in E-710, the single arm data used above for obtaining N_{inel} has a significant (~93%) background caused by, for example, beam-gas interactions. It was determined by using data taken with some of the antiproton and proton bunches missing, which allowed a statistically accurate determination of the background rate without colliding antiproton-proton events. As a check of our result, we also obtain consistent results by two alternate methods, given below, which do not use this technique.

(i) We can estimate the LR rate that we would have if we had 4π coverage by studying in the analysis stage the addition to our LR rate of other annular counters ($3.9 < |\eta| < 5.2$) and an extrapolation to η regions not covered. The ($3.9 < |\eta| < 5.2$) region adds 0.1005 ± 0.0016 of the LR rate, and the extrapolation adds 0.0212 ± 0.0214 of the LR rate. Note that both of these additions are small because the high multiplicity of inelastic events leads to about 90% of all LR events with at least one particle in the range $5.2 < |\eta| < 6.5$ on both sides. If we make the assumption that the inelastic cross section is composed of only double-arm events and single diffraction (as in Ref. 10), and use the $\sqrt{s} = 1.8$ TeV world average(13, 18, 19) single diffraction cross section of 9.45 ± 0.42 mb, we obtain $\sigma_T = 71.41 \pm 1.98$ mb.

(ii) We can use the CDF Monte Carlo calculation for their LR acceptance(10) for inelastic events in the range $3.2 < |\eta| < 6.7$. We have counters covering a somewhat similar range ($3.9 < |\eta| < 6.5$); however, the different beam pipe configurations of the two experiments, leading to different particle distributions due to interactions in the beam pipes, preclude a precise comparison. Nevertheless, we use the CDF Monte Carlo calculation to obtain our number of LR events for a 4π coverage, and add the world average single diffraction cross section (thus with the same assumption as in (i) above). The result is $\sigma_T = 72.3$ mb.

We quote as our final result $\sigma_T = 71.71 \pm 2.02$ mb; this is shown in Figure 1 together with earlier data(1-5,7-10). Also shown in the Figure is our σ_{el}, together with earlier data(4,5,7,11,13,20).

Our result is in good agreement with that of E-710(9), and differs by about 2.8 standard deviations from that of CDF(10); the confidence level that all 3 results are compatible is only 1.6%. Our result, together with the lower energy data, is consistent with a log(s) variation of σ_T with energy, rather than a $\log^2(s)$ variation. Also, using the approximate asymptotic dispersion relation(21)

$$\rho \approx \frac{\pi}{2\sigma_T} \frac{d\sigma_T}{d(\log s)} \tag{4}$$

our value of σ_T, together with lower energy data, gives a ρ value consistent with those measured(9,22) in this energy range.

In summary, we have made a new measurement of the proton-antiproton total cross section at $\sqrt{s}$ = 1.8 TeV, with higher precision than previously available. Our result, σ_T = 71.71 ± 2.02 mb, together with lower energy data, is consistent with a log(s) variation of σ_T.

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FIGURE CAPTION

Figure 1. a) Results for σ_T from this experiment and from previous(1-5,7-10) experiments; b) Results for σ_{el} from this experiment and from previous experiments(4,5,7,11,13,20).

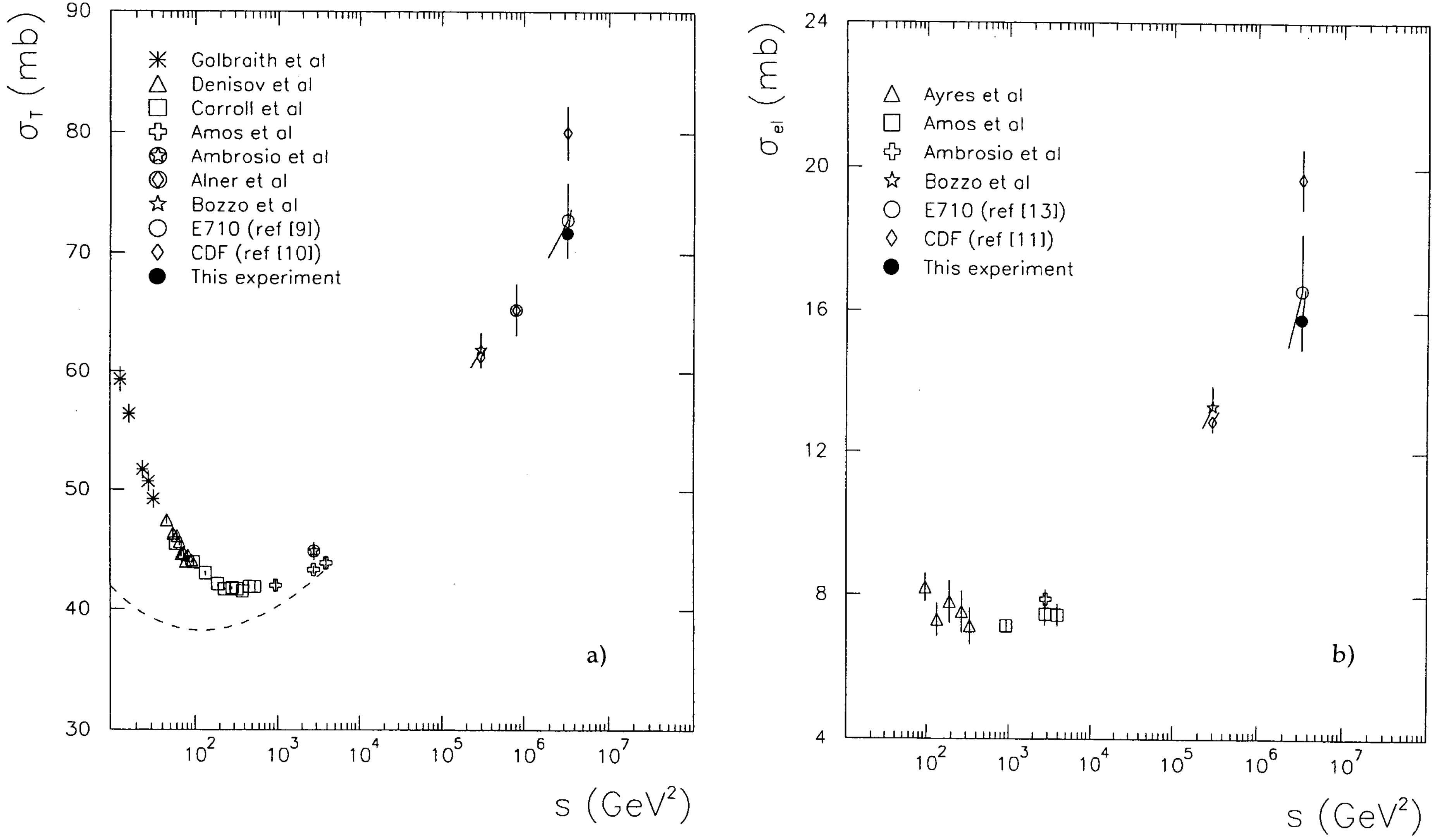
σ_T (mb)
90
80
70
60
50
40
30
Galbraith et al
Denisov et al
Carroll et al
Amos et al
Ambrosio et al
Alner et al
Bozzo et al
E710 (ref [9])
CDF (ref [10])
This experiment
a)
10^2
10^3
10^4
10^5
10^6
10^7
s (GeV^2)
σ_{el} (mb)
24
20
16
12
8
4
Ayres et al
Amos et al
Ambrosio et al
Bozzo et al
E710 (ref [13])
CDF (ref [11])
This experiment
b)
10^2
10^3
10^4
10^5
10^6
10^7
s (GeV^2)

Figure 1