

Measurement of ρ , the Ratio of the Real to the Imaginary Part of the $\bar{p}p$ Forward Elastic-Scattering Amplitude, at $\sqrt{s} = 1.8$ TeV

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(Received 7 October 1991)

We have measured ρ , the ratio of the real to the imaginary part of the $\bar{p}p$ forward elastic-scattering amplitude, at $\sqrt{s} = 1.8$ TeV. Our result, $\rho = 0.140 \pm 0.069$, is compared with extrapolations from lower-energy data based on dispersion relations, and with the UA4 value at $\sqrt{s} = 546$ GeV.

PACS numbers: 13.85.Dz

As part of our study of $\bar{p}p$ interactions at the Fermilab Tevatron Collider, we report here a measurement of ρ , the ratio of the real to the imaginary part of the forward $\bar{p}p$ elastic-scattering amplitude, at $\sqrt{s} = 1.8$ TeV. Because of the analyticity of the elastic-scattering amplitude, a determination of ρ , together with measurements of pp and $\bar{p}p$ total cross sections and some very general assumptions about the scattering amplitude, allows the behavior of total cross sections to be determined at much higher energies than are currently available.

Fits to ρ and σ_T available up to CERN ISR energies have been used in the above manner to predict values of ρ and σ_T at CERN SPS and Tevatron Collider energies [1,2]. The predictions for total cross sections were in agreement with measured values when they became available. However, the SPS UA4 measurement [3] at $\sqrt{s} = 546$ GeV of $\rho = 0.24 \pm 0.04$ was ~ 2.5 standard deviations from the expected value of ~ 0.14 . This possible discrepancy was discussed in many theoretical papers; some examples are given in Refs. [4–9]. There was a general consensus in these papers that some new physics was needed to accommodate a value of 0.24; predictions were given for σ_T and ρ at $\sqrt{s} = 1.8$ TeV, although some of the predictions were not consistent with our subsequent measurement [10] of σ_T at $\sqrt{s} = 1.8$ TeV.

Our apparatus has been described in earlier publications [10–13], to which reference can be made for details. In order to measure ρ , measurements of the elastic scattering $d\sigma/dt$ have to be made to very small $|t|$ values, around the t value where the maximum interference between Coulomb and nuclear scattering occurs. At our energy, this is at $|t| \approx 0.001$ (GeV/c)² which corresponds to a scattering angle of only 35 μ rad. Using the detectors in our outer “Roman pots” (see Fig. 1 of Ref. [11]), we were able to measure elastic scattering down to these an-

gles.

This measurement includes the same data as in our previously reported results, but with two additions. The first is that some more runs were analyzed, increasing the total integrated luminosity by almost 75%. The second is that we analyzed events in our detectors to within 2.75 mm of the beam center (the chamber extended down to 2.2 mm from the beam center). This allowed us to measure scattering at small enough $|t|$ values to obtain ρ , although background rates were large close to the beam. Data were analyzed over the range $0.001 \leq |t| \leq 0.14$ (GeV/c)², and our final sample contained 180000 elastic events.

Event selection has been described in our earlier publications. Because the drift chamber horizontal (x) coordinate readouts (based on charge division) were known with substantially less accuracy than the vertical (y) coordinate readouts, we integrated over x and only used the y coordinate in our analysis. Although each bin in y , after integrating over x , then covers a range of t values, it can be shown analytically that ρ can be obtained correctly from the data; this was also verified by Monte Carlo studies. There is some loss of statistical accuracy using this method, but it avoids the systematic uncertainties which would have been present in the result due to our x readout uncertainties. Note that the ends of the x integration are the precisely known edges of the trigger counters.

Elastic events were obtained from detectors in conjugate pot pairs BC or AD in the schematic arrangement shown in Fig. 1(a). Figure 1(b) shows for one run a scatter plot of the correlation for each event between the y coordinates of the detectors in pots A and D ; the elastic events can be clearly seen as the diagonal band, together with background close to the beam in either pot. To ob-

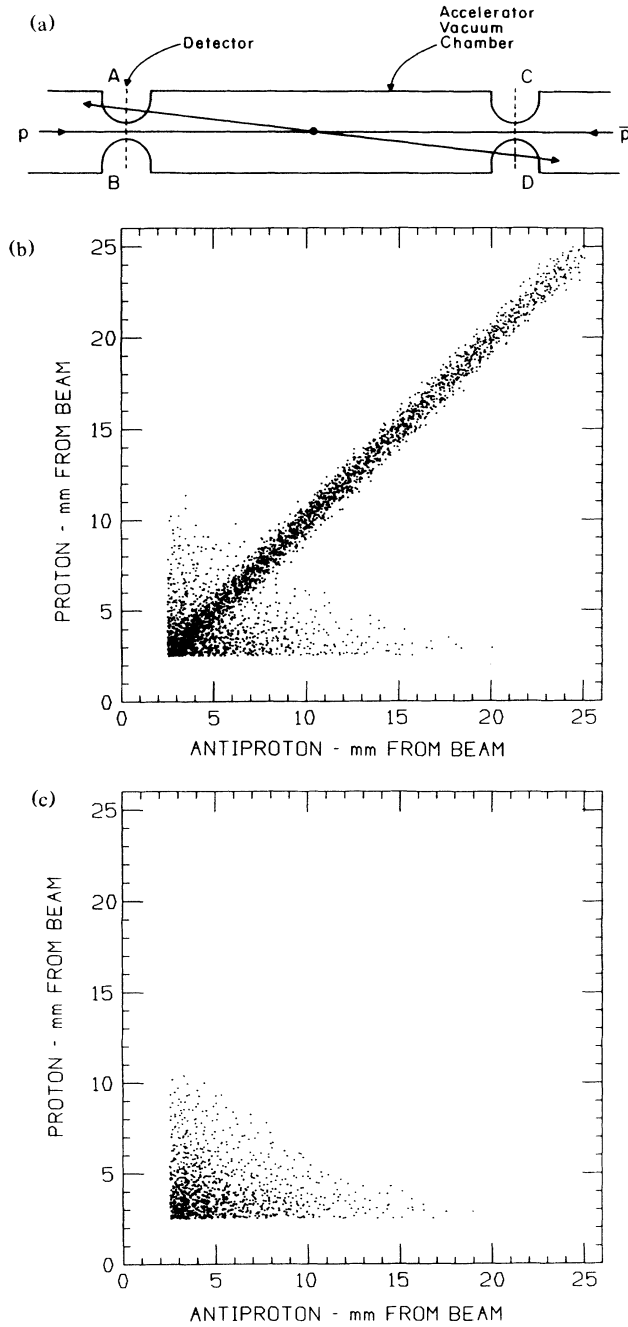


FIG. 1. (a) Schematic side view of the experiment, with detectors in the four pots *A, B, C, D*. (b) Scatter plot of the correlation for each event between the *y* coordinates in the detectors in pots *A* and *D*, for one run. (c) Scatter plot of background events in pots *A* and *D*, corresponding to the data of (b); see text for details.

tain backgrounds we used the nonconjugate pot pairs *AC* and *BD*. For example, the background in the *AD* combination was obtained from simultaneous data taken of the combinations *AC* (for detector *A*) and *BD* (for detector *D*). These two distributions were then combined to produce the *AD* background distribution shown in Fig.

1(c). We would expect that the background is due to uncorrelated hits in the chambers caused by, for example, beam halo, which is known to increase sharply close to the beam; the observed background rates are consistent with this. The background due to inelastic events is negligible, since the ~ 100 m of 4 T magnetic field between the interaction point and either detector limits particles reaching the detectors to be within $\sim 1\%$ of the circulating beam momentum. Extensive studies showed that the shape of the distribution in Fig. 1(c) is identical to that of the background in Fig. 1(b), as expected [14]. The background obtained in this way was normalized to that in the conjugate pot distribution combinations outside the elastic region, and subtracted bin by bin. In some runs the background at our lowest *y* (vertical distance from beam center) bin was almost equal to the elastic signal, although it dropped by a factor of 10 in 2.75 mm. However, using the method described above, the background was determined even in the worst case to an accuracy of $\pm 3\%$.

We use the following expression for the elastic differential cross section:

$$\frac{1}{L} \frac{dN_{el}}{dt} = \frac{d\sigma}{dt} = \frac{4\pi a^2 (\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho - \alpha\phi)\sigma_T G^2(t)}{|t|} \exp(-B|t|/2) + \frac{\sigma_T^2(1+\rho^2)}{16\pi(\hbar c)^2} \exp(-B|t|). \quad (1)$$

The three terms in Eq. (1) are due to, respectively, Coulomb scattering, Coulomb-nuclear interference, and nuclear scattering. *L* is the integrated accelerator luminosity, dN_{el}/dt is the observed elastic differential distribution, α is the fine structure constant, ϕ is the relative Coulomb-nuclear phase, given by [15] $\ln(0.08|t|^{-1} - 0.577)$, and $G(t)$ is the nucleon electromagnetic form factor, which we parametrize in the usual way as $(1 + |t|/0.71)^{-2}$ [*t* is in (GeV/*c*)²].

We also use the following two equations:

$$\sigma_T^2 = \frac{1}{L} \frac{16\pi(\hbar c)^2}{1+\rho^2} \left. \frac{dN_{el}^n}{dt} \right|_{t=0}, \quad (2)$$

$$\sigma_T = \frac{1}{L} (N_{el}^n + N_{inel}). \quad (3)$$

Equation (2) is obtained from the optical theorem. N_{el}^n is the total number of nuclear elastic events, obtained from the observed dN_{el}/dt distribution in the *t* region where nuclear scattering dominates, and extrapolated to $t=0$ and $t=\infty$ using the form $\exp(-B|t|)$. $dN_{el}^n/dt|_{t=0}$ is the observed differential number of nuclear elastic events extrapolated to $t=0$ using the same form. N_{inel} is the total number of inelastic events; our method for obtaining this, using detectors close to the interaction point, has been described earlier [10]. Note that Eqs. (2) and (3) allow us to express *L* in terms of σ_T and ρ . Then dN_{el}/dt in Eq.

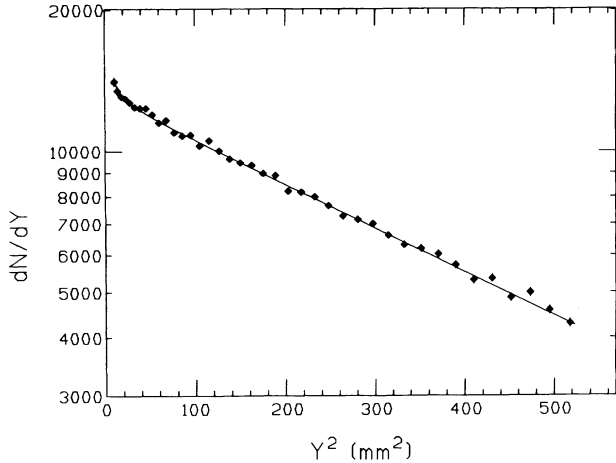


FIG. 2. Results of this experiment for the elastic-scattering distribution dN/dy vs y^2 , for almost all of the data. The best-fit curve described in the text is shown.

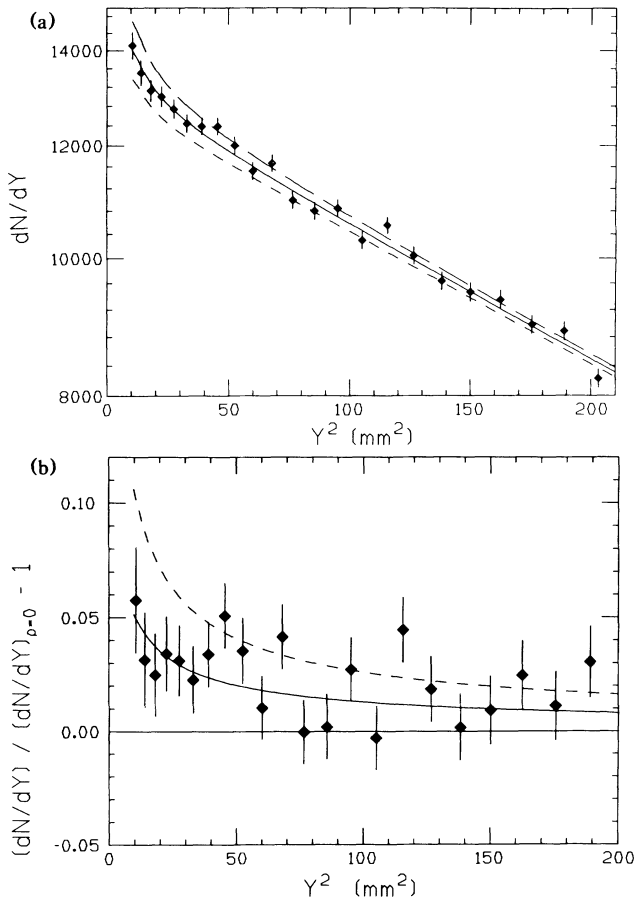


FIG. 3. (a) As for Fig. 2, with only data for $y^2 < 210 \text{ mm}^2$. The solid curve is the best fit described in the text ($\rho = 0.140$); the long-dashed and short-dashed curves show values of ρ of 0.280 and 0, respectively (see text for details). (b) The same data as in (a), given in a form to show the deviation of the data and the best fit ($\rho = 0.140$) from $\rho = 0$ (horizontal line) and $\rho = 0.28$ (dashed curve).

(1) can be expressed in terms of just three unknowns: σ_T , B , and ρ . Our input data are our measurements of dN_{el}/dt together with the total number of inelastic events N_{inel} for the same runs as for the elastic data. We do a least-squares analysis for σ_T , B , and ρ in Eq. (1) using all our input data [16]. As explained earlier, this procedure was modified in practice, although not in principle, because, instead of using measurements of dN_{el}/dt as input, we used dN_{el}/dy where y is the vertical distance from the beam center, and where each y bin covers a specified range of t .

The result obtained from the three-parameter least-squares fit is

$$\rho = 0.140 \pm 0.069, \quad B = 16.99 \pm 0.47 \text{ (GeV/c)}^{-2},$$

$$\sigma_T = 72.8 \pm 3.1 \text{ mb}.$$

The analysis procedure has been designed so that the errors are almost totally statistical [17]. The χ^2 per degree of freedom (D.O.F.) of the fit is 1.3.

The values of B and σ_T given above are consistent, within the quoted errors, with our earlier values [10, 12, 13], and supersede them. None of our earlier physics conclusions is substantially altered. We show in Fig. 2 all of our dN_{el}/dy data as a function y^2 , together with our fit. Figure 3(a) gives the same data in the small y region, together with our fit and two curves showing the effect of changing ρ , but keeping B and $\sigma_T(1+\rho^2)$ fixed. [Note that B and $\sigma_T(1+\rho^2)$ are essentially determined from the larger y data.] Figure 3(b) shows the same information displayed in the manner used by Ref. [3]. We note again that the figures show dN_{el}/dy with each y bin corresponding to a range of t ; for example, our smallest y bin covers the range $0.00095 \leq |t| \leq 0.0777 \text{ (GeV/c)}^2$, and our largest covers $0.0651 \leq |t| \leq 0.1431 \text{ (GeV/c)}^2$.

We have verified that our result for ρ is stable when we change the lowest y of the data used in the fit from 2.75

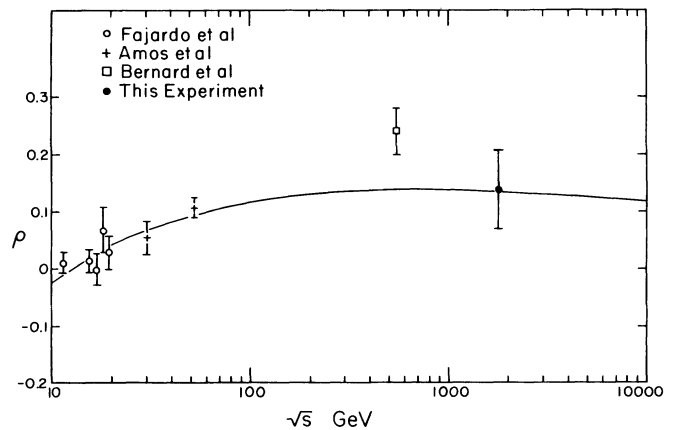


FIG. 4. Our result for ρ , together with results from lower energies (Refs. [3, 18, 19]), and a curve (Ref. [20]) showing the prediction based on existing pp and $\bar{p}p$ and σ_T and ρ data except for the ρ value at $\sqrt{s} = 546 \text{ GeV}$.

to 4.25 mm from the beam center (ρ is always between 0.13 and 0.17 with no correlation with the lowest y). Since backgrounds in our data are reduced by a factor of ~ 3 in that y range, this gives us confidence in our background subtraction technique. The result is also constant ($\chi^2/\text{D.O.F.} = 0.5$) over four data sets taken from our two data-taking runs which were separated by about a month.

Our result for ρ is shown in Fig. 4, together with results at lower energies [3,18,19], and a curve [20] showing the prediction based on previously existing pp and $\bar{p}p$ σ_T and ρ data except for the ρ value at $\sqrt{s} = 546$ GeV. There are recent models (e.g., Ref. [7]) which can fit both our ρ value and that of UA4 at $\sqrt{s} = 546$ GeV, although from Fig. 4 it can be seen that no new physics is needed to fit our result by itself.

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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[17] The uncertainty in ρ is due almost entirely to the following: fit of Eq. (1) to the data (± 0.048), background subtraction (± 0.043), effective x distance to the detectors (± 0.008), and effective y distance to the detectors (± 0.007). All of these except the effective x distance have been determined from our own data with each uncertainty in a quantity being the statistical accuracy with which we determined that quantity.

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