Fermi National Accelerator Laboratory

FERMILAB-Conf-91/277

FNAL/C--91/277

DE92 002647

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

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October 1991

* Presented at the *Joint International Lepton-Photon Symposium Europhysics Conference on High Energy Physics*, Geneva, Switzerland, July 25-August 1, 1991.

MEASUREMENT OF THE RATIO OF THE REAL TO THE IMAGINARY PART OF THE FORWARD NUCLEAR AMPLITUDE FOR $p\bar{p}$ ELASTIC SCATTERING AT $\sqrt{s} = 1.8$ TeV

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ABSTRACT

Experiment E710 at Fermilab has measured the ratio of the real to the imaginary part of the forward nuclear elastic scattering amplitude, ρ, for $\bar{p}p$ elastic scattering at $\sqrt{s} = 1.8$ TeV. The result is $\rho=0.140\pm.069$.

Introduction

The elastic differential cross section for $\bar{p}p$ scattering is given by a sum of three terms - a Coulomb term, a nuclear term and an interference term.

$$\frac{d\sigma_c}{dt} = \frac{4\pi\alpha^2(\hbar c)^2 G^4(t)}{|t|^2} \qquad (1)$$

$$\frac{d\sigma_n}{dt} = \frac{\sigma_t^2(1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|} \qquad (2)$$

$$\frac{d\sigma_{cn}}{dt} = \frac{\alpha(\rho-\alpha\phi)\sigma_t G^2(t)}{|t|} e^{B|t|/2} \qquad (3)$$

where, G(t) is the electromagnetic form factor of the proton, σ_t is the total nuclear cross section, B is the nuclear slope parameter, ρ is the ratio of the real to the imaginary part of the forward nuclear elastic scattering amplitude, ϕ is the phase of the Coulomb amplitude relative to the nuclear amplitude[1], and α is the fine structure constant. The scattering is dominated by the Coulomb term at small $|t|$ and by the nuclear term at learger $|t|$. Measurements in some intermediate range around $|t|=.001$ $(GeV/c)^2$, where the interference term is significant, are required for determining ρ.

dN/dt in terms of N_{inel}, σ_t, ρ and B

The t-distribution of elastically scattered particles is given by,

$$\frac{dN}{dt} = L\frac{d\sigma}{dt} \qquad (4)$$

where L is the luminosity. Writing the total nuclear interaction rate, $N_t=L\sigma_t$, as the sum of the nuclear elastic rate N_n, and the inelastic rate N_{inel}, we have,

$$N_n + N_{inel} = L\sigma_t \qquad (5)$$

The total nuclear elastic rate is,

$$N_n = \int_0^\infty d|t| \frac{\sigma_t^2(1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|}$$
$$= L\frac{\sigma_t^2(1+\rho^2)}{16\pi(\hbar c)^2 B} \qquad (6)$$

Substituting eq. 6 into eq. 5, we get,

$$L = N_{inel}\left[\sigma_t\left(1-\frac{\sigma_t(1+\rho^2)}{16\pi B(\hbar c)^2}\right)\right]^{-1} \qquad (7)$$

Using eq. 7 for luminosity, we can write the differential cross section given by eqs. 1, 2 and 3, in terms of N_{inel}, σ_t, ρ and B.

Data taking for elastic events.

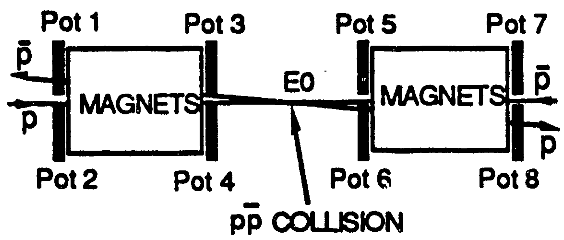

Fig 1 Elastic Scattering Detectors (pots).

The location of the elastic scattering detectors is shown schematically in figure 1. The detectors are described in ref. [2]. Elastic events have particles detected in pots 1 and 8 or pots 2 and 7. The data were taken in dedicated runs during two periods in November 1988 and December 1988. Six proton bunches collided with six antiproton bunches. The beams were scraped to enable the pots to be placed at small scattering angles. The luminosity was $\sim 10^{26} cm^2 s^{-1}$. The active region of the chambers was 2.2 mm from the center of the beam. The detectors covered the t-range $0.0006 \le |t| \le 0.142$ $(GeV/c)^2$.

The Scattering Angle.

The projection of the scattering angle in the horizontal plane, θ_x, can be written in terms of the displacement, x, of the scattered particle from the ideal orbit, recorded at the detector, the displacements x_0 and z_0 in the x and z directions of the collision from the center of the collision region, the initial angle α_x of the colliding particle with respect to the ideal orbit, and the transport matrix elements between the center of the interaction region and the detector, L_x and m_x, as, $\theta_x = (x - X_0)/L_x$, $\theta_y = (y - Y_0)/L_y$, with

$$X_0 = \delta x + m_x x_0 + \alpha_x L_x$$

$$Y_0 = \delta y + m_y y_0 + \alpha_y L_y$$

where δx is the difference between the actual position of the particle at the detector and the recorded position, due to the resolution of the detector.

Function fit to y-distributions

We define,

$$f\left(\frac{(x-X_0)^2}{L_x^2} + \frac{(y-Y_0)^2}{L_y^2}\right) = \frac{p^2}{L_x L_y} F(p^2\theta^2)$$

where p is the momentum of the incident particle, and for small θ, F is given by the sum of eqs 1, 2 and 3.

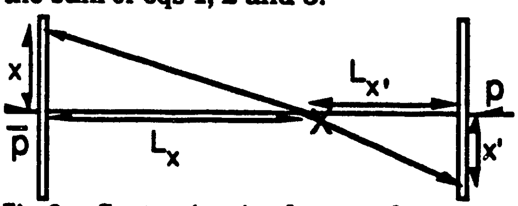

Fig 2. Scattering in the x-z plane.

The number of elastic events in which a scattered particle strikes a strip of width dy while the other particle strikes the other detector, is given by,

$$\frac{dN}{dy} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{x_1}^{x_2}\int_{x'_1}^{x'_2}\int_{y'_1}^{y'_2} dX_0\, dY_0\, dx\, dx'\, dy'$$

$$\times \frac{\exp(-X_0^2/2\sigma_{X_0}^2)}{\sqrt{2\pi}\sigma_{X_0}} \frac{\exp(-Y_0^2/2\sigma_{Y_0}^2)}{\sqrt{2\pi}\sigma_{Y_0}}$$

$$\times f\left[\frac{(x-X_0)^2}{L_x^2} + \frac{(y-Y_0)^2}{L_y^2}\right]$$

$$\times \frac{\exp\left[-\{x - X_0 - (x' L_x / L_{x'})\}^2 / 2\sigma_{x'}^2\right]}{\sqrt{2\pi}\sigma_{x'}}$$

$$\times \frac{\exp\left[-\{y - Y_0 - (y' L_y / L_{y'})\}^2 / 2\sigma_{y'}^2\right]}{\sqrt{2\pi}\sigma_{y'}}$$

where x_1 and x_2 are the x-limits of the detector in pot 1, and x_1', x_2' and y_1', y_2' are the x and y limits of the detector in pot 8. We have taken the distributions in X_0 and Y_0 to be gaussians with widths σ_{X0} and σ_{Y0} respectively. The integral can be written as a sum of terms each of which factorizes into a function of y and a function of N_{inel}, σ_t, ρ and B.

$$\frac{dN}{dy} = \sum_i E_i'(N_{inel}, \sigma_t, \rho, B) K_i(y) \qquad (8)$$

This function, with N_{inel} determined from our measurement of the inelastic interaction rate, was fit to the experimental distributions to extract the values of σ_t, ρ and B. The measurement of the inelastic rate is described in ref. [3]. The effective lengths and beam- widths in the y-z plane, were determined using elastic events in which scattered particles went through pots 1, 3, 6 and 8. The corresponding quantities for the x-z plane were obtained from the Accelerator Group.

y-distribution of Elastic Events

Fig 3 shows the y-coordinate for the particle in pot 1 plotted against the y-coordinate recorded in pot 8 for our elastic candidates. The elastic events lie along the positive diagonal. We see background events close to the beam. The background was approximately equal to the signal at 3 mm from the beam.

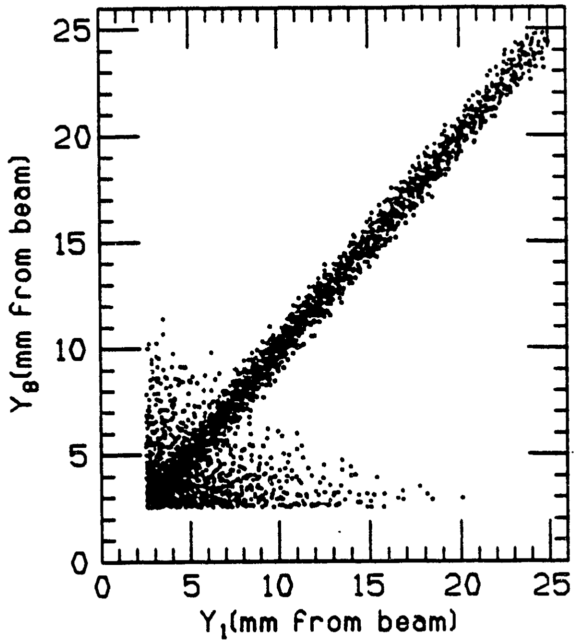

Fig 3. y_1 vs y_8 for elastic candidates.

Due to the narrow momentum acceptance (<1%) of the Tevatron, we do not have a significant background arising from inelastic $\bar{p}p$ collisions in our elastic sample. The background in our elastic distribution is due to uncorrelated pairs of particles in the two pots of an elastic combination. The background in the elastic sample, where the particle in pot i is at $y=y_{ik}$ and that in pot j is at $y=y_{jl}$, can be written as,

$$B_{ij}(y_{ik}, y_{jl}) = cF_i(y_{ik})F_j(y_{jl}) \quad (9)$$

where $F_i(y_{ik})$ describes the shape of the distribution of background particles in pot i, and c is a normalization constant. The distributions $F_i(y_{ik})$ for the various pots were obtained from events in which particle pairs were recorded in pots 1 and 7 or pots 2 and 8. The constant c was obtained by dividing the number of events in an off-diagonal region in fig 3, by an integral of the function in eq. 9 over the same region.The background was then subtracted from our elastic event sample. The y-distribution of the remaining events in pots 1 and 2, was corrected for detector and trigger inefficiencies. The nuclear part of the resulting distribution was fit to a gaussian to determine the forward direction in the y-z plane. Finally, the distribution of the y-coordinates measured from this forward direction was fit to the function in eq 8 to obtain σ_t, ρ and B. Fig 4 shows the y-distribution of all our data with the best-fit curve superimposed. The result, including all uncertainties, is, $\sigma_t = 72.8 \pm 3.1$ mb, $\rho = 0.140 \pm .069$, and $B = 16.99 \pm .47 (\mathrm{GeV}/c)^{-2}$.

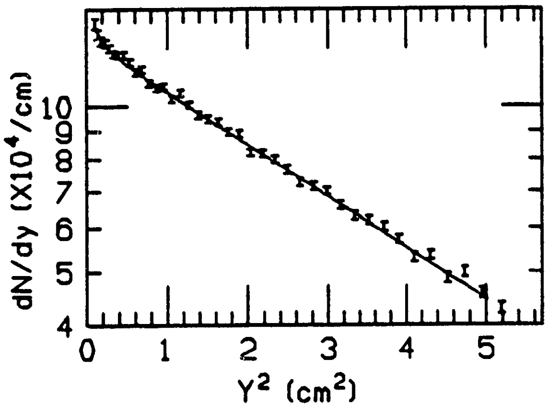

Fig 4. y-distribution of elastic events.

Conclusions

The values we obtain for σ_t and ρ are compatible with parametrizations of σ_t that have the pp and $\bar{p}p$ cross sections becoming equal and going smoothly into a $\log^2 s$ behavior at very high energies[4,5].

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