400-GeV/c pp Elastic Scattering: Energy and Angle Dependence at High Momentum Transfer

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Proton-proton elastic scattering at 400 GeV/c has been measured in the region $5.4 < -t < 14.4$ GeV^2 with no sign of a second dip or "break." If the data are fitted by $\exp(At)$, the slope A decreases from 1.5 ± 0.1 to 0.7 ± 0.2 GeV^{-2} over the range. At fixed t the 400-GeV/c cross sections are about 0.6 times those at 200 GeV/c in this t range. At fixed $\theta_{c.m.} = 15°$, $d\sigma/dt \propto s^{-n}$ where $n = 9.7 \pm 0.3$.

Results from the CERN intersecting storage rings[1] show that $d\sigma/dt$ is essentially independent of s in the region $500 < s < 3800$ GeV^2 up to $-t \approx 4$ GeV^2. (The only s dependence is a small shift in the dip at $-t \approx 1.4$ GeV^2.) This raises the question whether the asymptotic region has been reached for all values of t when $s > 500$ GeV^2 (a fixed-target beam momentum of 280 GeV/c). Results of the present experiment show that for $-t > 6$ GeV^2 there is still a significant energy dependence, but that it is decreasing with increasing s. In addidtion there is no evidence for a predicted second dip[2] or for a slope of $d\sigma/dt$ consistent with diffraction scattering.[3]

The experiment was performed in the proton west area of the Fermi National Accelerator Laboratory using the same apparatus shown in Fig. 1 of the previous Letter reporting our 201-GeV/c results.[4] The only significant difference was the use of a third analyzing magnet in the forward spectrometer. The acceptances and resolutions were comparable in both experiments, and most of the normalization errors cancel when taking the ratio of the 200- to the 400-GeV/c cross sections. Typical beam intensities were $\sim 5 \times 10^{11}$ protons per pulse with a spot size of ± 1.9 mm rms and beam divergence of $\pm 6 \times 10^{-5}$ radians at the target. The limitation on beam intensity was due to accidental triggers which were not allowed to exceed 30 per pulse. At 400 GeV/c three different settings of the forward spectrometer and target position were necessary in order to cover the entire t range. The low-t run covered $5.4 < -t < 9.2$ GeV^2, the mid-t run covered $8.4 < -t < 12.8$ GeV^2, and the high-t run covered $10.0 < -t < 14.4$ GeV^2. The 200-GeV/c running took place between the mid-t and high-t runs. All running took place in one uninterrupted block of time. Results from the three individual 400-GeV/c runs are shown in Fig. 1 plotted against p_t. Since the absolute cross sections in the regions of overlap agree within errors, the overlapping cross sections have been combined sta-

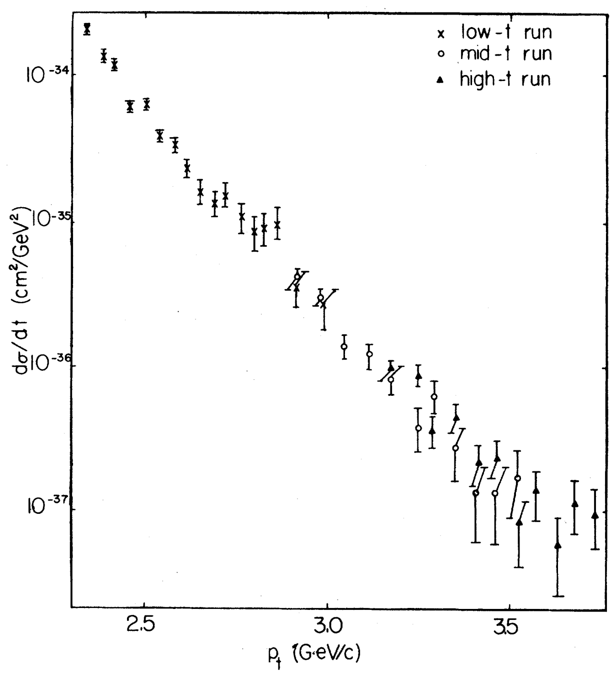

FIG. 1. 400-GeV/c results for the three geometries of this experiment plotted vs p_t. Only statistical errors are shown. There is in addition a 20% normalization error.

tistically and are shown in Fig. 2 where $d\sigma/dt$ is shown as a function of t together with other results from 19.3,[5] 21.3,[6] 28,[7] and 1496 GeV/c.[8]

We use Fig. 3 to illustrate the low level of inelastic background at even the highest t. Figure 3(a) shows those events in the high-t run which have at least one track in each spectrometer arm which can be tracked back to the target. No other cuts have been made. The dashed line shows a possible interpolation of inelastic events under the elastic peak leading to an estimate of ~ 60% background before making the remaining cuts. Figure 3(b) shows that when coplanarity, $t_{\text{forward}} - t_{\text{recoil}}$, opening-angle, and recoil missing-mass cuts are made, the inelastic background drops down to (4 ± 1)%. (More details on the cuts and the experimental setup are given in Ref. 4.) Inelastic background in the mid-t run was (6 ± 2)%. In the low-t run the scattering angles were too small to allow room for proper collimation between the beam and scattered protons. Because of this the inelastic background rose to (12 ± 2)% for the low-t run. Figure 3(a) also shows that in the worst case ~ 3% of the triggers which contained tracks originating in the target were elastics.

The efficiencies of all multiwire proportional chambers were continuously monitored and averaged about 94% per plane. The resulting probability that our system miss either the forward or recoil track was 12%. Cross sections were corrected for this 12% loss and an additional 17% loss due to particle absorption in the air path and detectors. Reconstruction loss was about 2%. Loss due to elastic cuts was (5 ± 2)%. Beam monitoring was the same as in Ref. 4 with an overall 20% (rms) normalization uncertainty. This uncertainty is reduced to ~ 5% when taking ratios of the 200- to 400-GeV/c cross sections. The rms

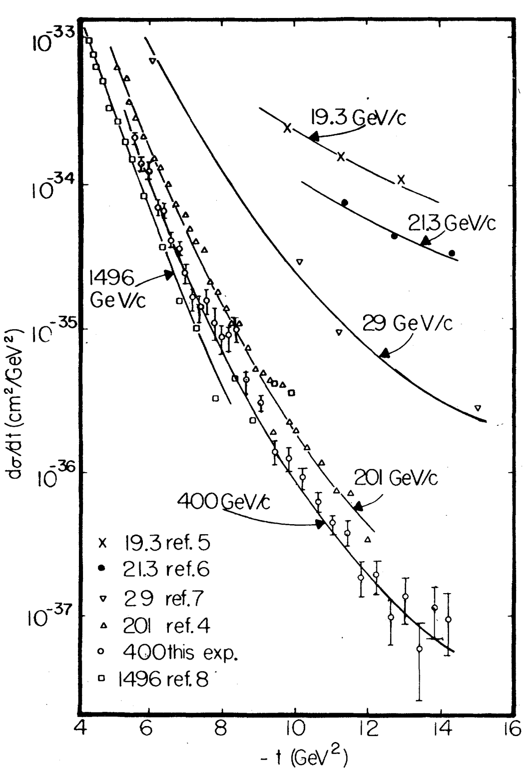

FIG. 2. Combined results of our 400-GeV/c experiments plotted vs t along with our 201-GeV/c results (Ref. 4) and results of other experiments (Refs. 5–8). The curves are drawn to guide the eye.

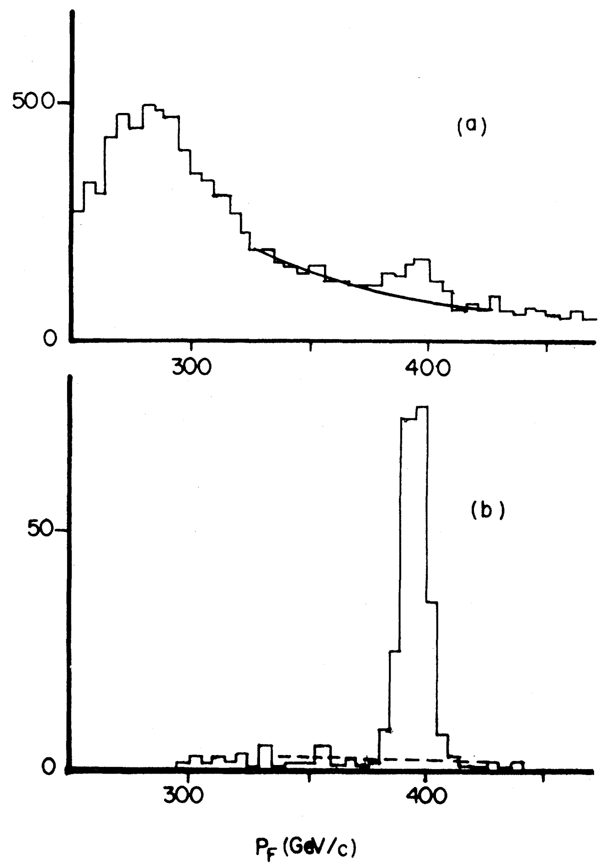

FIG. 3. Number of elastic candidates from our highest-t run plotted vs p_f, the momentum as measured by the forward spectrometer. The momentum-transfer range is $10.0 < t < 14.4$ GeV^2. (a) All events where there is at least one track in each arm appearing to originate from the target. (b) Same conditions as in (a) except that all elastic cuts have been made except p_f. The dashed lines shows our estimate of the inelastic background under the elastic peak.

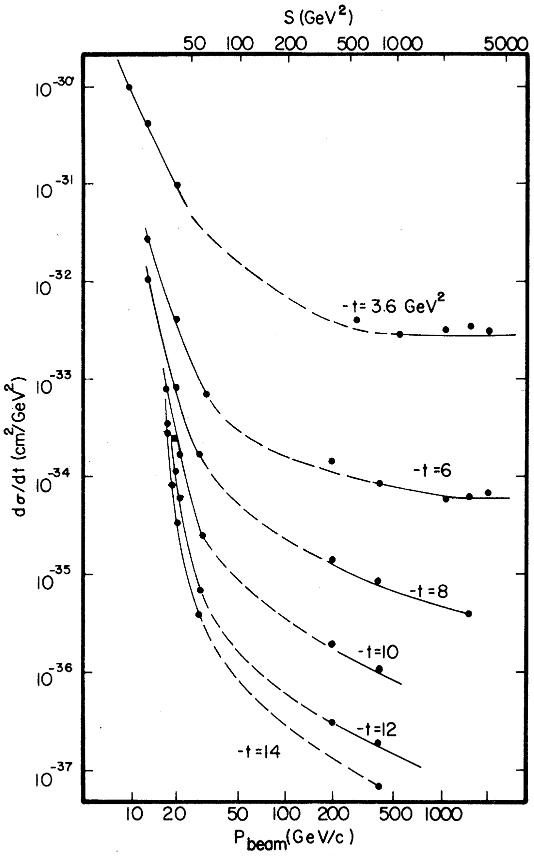

FIG. 4. $\ln d\sigma/dt$ vs $\ln P_{\text{beam}}$ for $-t=3.6$, 6, 8, 10, and 12 GeV^2. Some of the points shown are interpolations from nearby experimental points. The curves are drawn to guide the eye. Some of the unpublished results of Ref. 1 are used.

spread of the t determination is about $\pm 0.34\ \text{GeV}^2$ at $-t=5\ \text{GeV}^2$; it decreases linearly to about $\pm 0.15\ \text{GeV}^2$ at $-t=7\ \text{GeV}^2$; and then increases linearly to $\pm 0.19\ \text{GeV}^2$ at $-t=14\ \text{GeV}^2$. The absolute calibration of t is accurate to within one bin width. This uncertainty is due mainly to a $\pm 1\%$ variation in the momentum of the primary beam. A shift in the t scale of one bin width could cause a maximum change of $d\sigma/dt$ of $\sim 20\%$.

The initial slope $d(\ln d\sigma/dt)/dt$ of our 400-GeV/c results is found to be $1.5 \pm 0.1\ \text{GeV}^{-2}$ at $-t=6\ \text{GeV}^2$ and it gradually drops to $0.7 \pm 0.2\ \text{GeV}^{-2}$ at $-t \approx 12\ \text{GeV}^2$. As seen in Fig. 1, much of this change in slope is removed it the data are plotted vs p_t. Then the best fit is $d\sigma/dt = 3.2\times 10^{-28} \times \exp(-6.2 p_t)\ \text{cm}^2/\text{GeV}^2$. In diffraction scattering, the average slope following the first dip should be $\sim 5\ \text{GeV}^{-2}$.[3]

Figure 2 shows that $d\sigma/dt$ fixed t is still dropping with energy. At all values of t shown, the ratio of $d\sigma/dt$ at 400 GeV/c to that at 200 GeV/c is about 0.6 ± 0.2. At any fixed value of t, $d\sigma/dt$ drops with energy, but the rate of drop decreases rapidly with beam momentum. The power-law dependence of this decrease is given by the slopes of the curves in Fig. 4 where $\ln(d\sigma/dt)$ is plotted vs $\ln p_{\text{lab}}$. We see that at $-t=3.6\ \text{GeV}^2$ the asymptotic region is not reached until $p_{\text{lab}} \sim 1000$ GeV/c. At higher $|t|$ it appears that one must go to increasingly higher energies in order to achieve energy independence.

The s dependence of $d\sigma/dt$ at constant center-of-mass angle θ can be obtained from our results. For fixed θ, our 200- and 400-GeV/c results overlap only in the region 13° to 15° where we find $n = 9.1 \pm 0.3$ at 13° and 9.7 ± 0.3 at 15° for the form $[d\sigma/dt]_{\theta=\text{const}} \propto s^{-n}$. At 15° this is in agreement with the constituent-interchange model which predicts $n=10$.[9] Whether $n=10$ would work for larger angles at this energy is not known.

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