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Total, Elastic and Diffractive Cross Sections at High Energies *

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TOTAL, ELASTIC AND DIFFRACTIVE CROSS SECTIONS AT HIGH ENERGIES

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Abstract

The status of hadron-hadron total, elastic and diffractive scattering is discussed, including recent data from Fermilab experiment E- 710.

1. Introduction

This report will briefly review the state of hadron-hadron total, elastic and diffractive cross sections through the 1960's (data from the CERN PS and the BNL AGS), the 1970's (CERN ISR and Fermilab) and the 1980's (CERN SPS collider). We discuss the unanswered questions that existed in the field at that time. We then give a mid-1990 progress report on experiment E-710 at the Fermilab Collider, including a description of the experimental method and the results to date. Finally, we will discuss future prospects in this field.

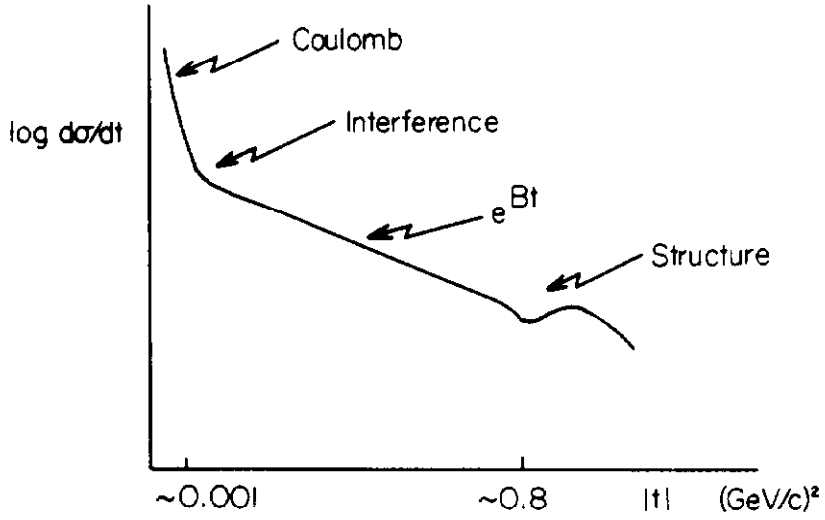

Figure 1. Typical elastic scattering distribution at hadron collider energies

In Figure 1, we show the typical elastic scattering distribution at collider energies, showing:

(i) the Coulomb region, where $\frac{d\sigma}{dt} \sim \frac{1}{t^2}$; this known cross section can be used for normalization,

(ii) the Coulomb-nuclear interference region at $|t| \sim 0.001$,[1] used to obtain ρ, the ratio of the real to imaginary part of the forward scattering amplitude,

(iii) the "diffraction peak" where $\frac{d\sigma}{dt} \sim e^{Bt}$ (B can be a function of both s and t), which can be extrapolated to $t = 0$ to obtain σ_T,

(iv) the structure region (dips and bumps), starting at $|t| \sim 0.8$.

There is a relationship between σ_T and B; for example, scattering from a black disc of radius R gives $B = R^2/4$, $\sigma_T = 2\pi R^2$, $\frac{\sigma_{el}}{\sigma_T} = 0.5$. Also ρ and σ_T are connected by dispersion relations.

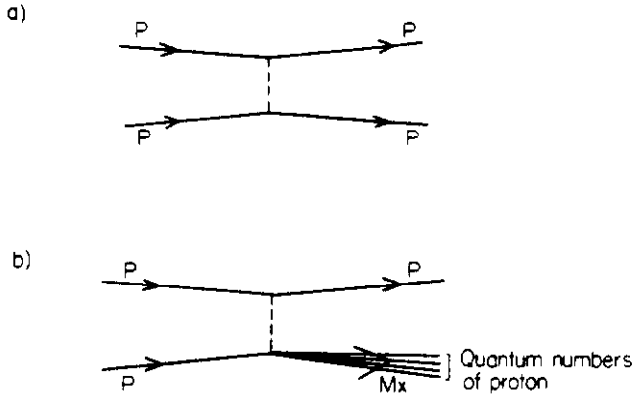

Figure 2. Feynman diagrams for a) elastic scattering, b) diffraction dissociation

Figure 2 shows the very similar Feynman diagrams for elastic scattering and (single) diffraction dissociation, where in the latter process one of the incoming particles dissociates into a number of particles, whose combined quantum numbers are the same as those of the incident particle.

2. Historical Review

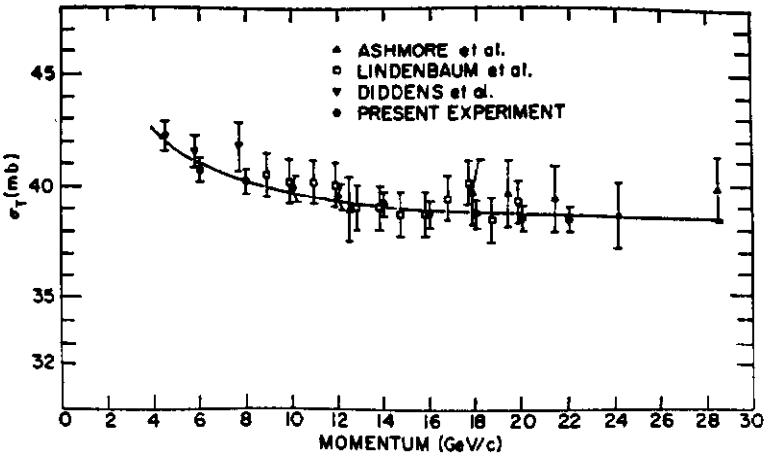

Figure 3. Total cross section for pp scattering, from Reference 2 (1965)

Figure 3 shows the typical energy dependence of a hadron-hadron cross section obtained in the mid 1960's[2]; at that time the data were consistent with the belief that all cross sections would eventually approach constant values as $s \rightarrow \infty$; this was in agreement with the then prevalent Regge-pole theory. However by the 1970's, the picture had changed - as s increased, all cross sections fell, reached a minimum and then rose[3] (Figure 4).

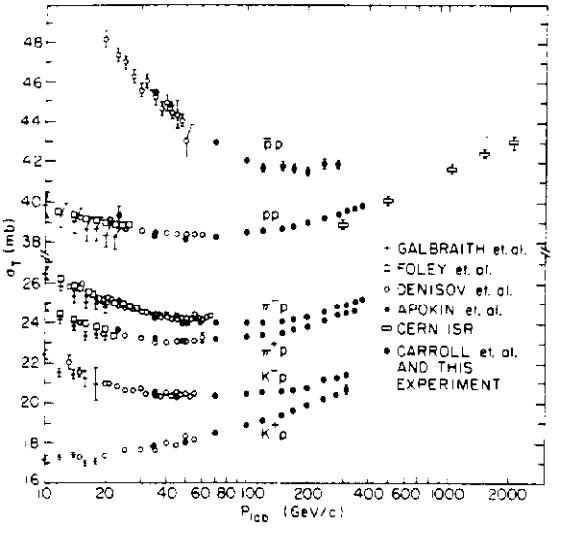

Figure 4. Hadron-hadron total cross sections, from Reference 3 (1979)

Using ISR measurements of ρ and σ_T , predictions for σ_T at higher energies could be made using dispersion relations; these showed σ_T rising until at least $\sqrt{s} \approx$ 500 GeV (Figure 5).

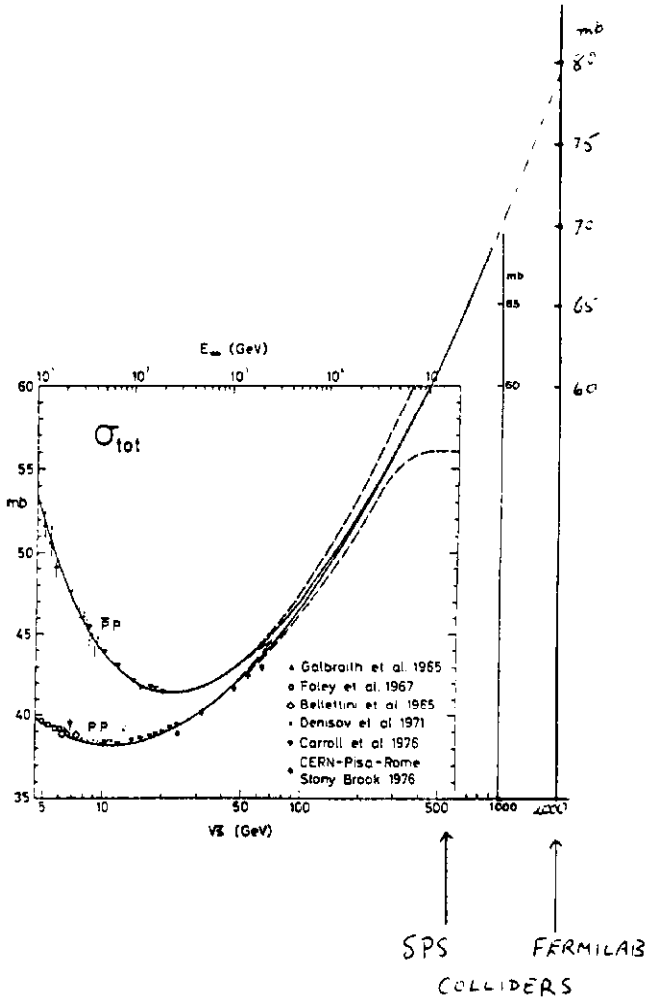

Figure 5. Total cross sections for pp and $\bar{p}$p, and prediction; from Fermilab E-710 proposal (1981)

There have been many explanations for the rising cross sections given in the past; these include an increase in diffraction scattering, minijets, and the increasing effect of gluons; however there is no universally accepted explanation, and QCD has not provided one. The rise is observed to be proportional to $\log^2 s$, the fastest possible consistent with analyticity (the Froissart bound).

An obvious question, both in the 1970's and also still relevant now, is: does σ_T continue to rise, becoming infinite at infinite energy, or does it eventually approach a constant value?

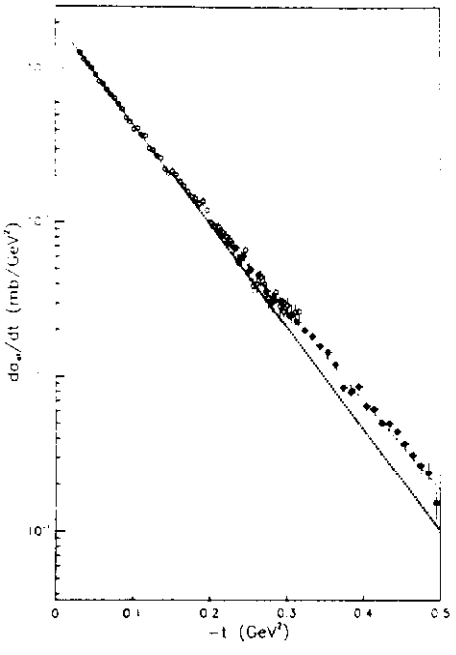

Figure 6. $\bar{p}p$ elastic scattering data from UA4 (Ref. 4).

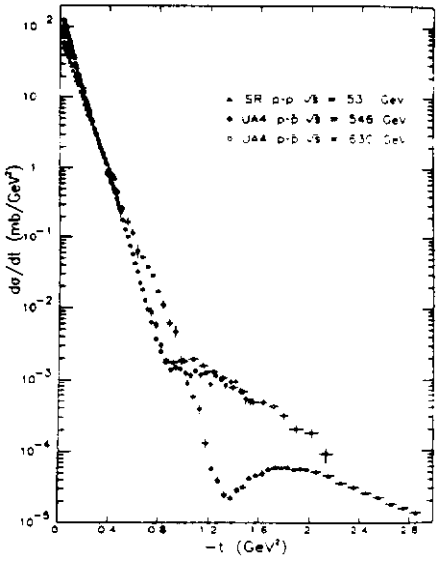

Figure 7. $\bar{p}p$ and pp elastic scattering data, from Refs. 6, 7 and 8.

In the early and mid 1980's, results became available from the CERN SPS collider; especially relevant are those from the UA4 experiment. Figure 6 shows some UA4 $\bar{p}p$ elastic scattering data[4] at $\sqrt{s} = 546$ GeV. Note that B is not constant, but decreases as a function of increasing $|t|$. In contrast, a black disc gives a pattern which goes to zero at some value of t, so that B increases as a function of $|t|$. This point will be returned to later. At the ISR and lower energies, $\frac{\sigma_{el}}{\sigma_T}$ is approximately constant at ~ 0.17, while UA4 measured[5] 0.21. The value of σ_{el}/σ_T is a measure of nucleon blackness and thus UA4 showed that the nucleon is becoming blacker with increasing energy, although at SPS

energies the ratio has not yet reached the black disc value of 0.5. Larger $|t|$ data[6,7,8] from the ISR and the SPS are shown in Figure 7. A dip or at least an abrupt change of slope appears in the region of $|t| \sim 0.8 - 1.20$, with the actual t value depending on energy. At $|t|$ values higher than this region, B becomes a more complex function of $|t|$. The t position of the dip or break at a given energy is roughly inversely proportional to the total cross section at that energy; this would be expected from some simple models. For example, a black disc with only one adjustable parameter, namely radius, which is a function of s, would exhibit this behavior.

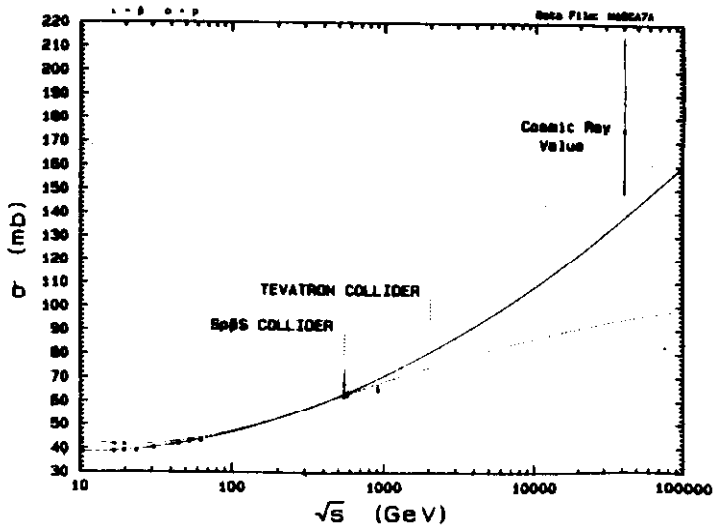

Figure 8. Fits to $\bar{p}p$ and pp total cross sections, from a later version of Reference 10. The solid curve increases as $\log^2 s$, while the dotted curve approaches a constant value.

Figure 8 shows the SPS collider values[5,9] of σ_T, together with fits[10] to all the then available data on σ_T and ρ for both pp and $\bar{p}p$. These fits are very general and model independent, using essentially only analyticity and unitarity. The data are not

able to distinguish between cross sections which at large s continue as $\log^2 s$, or those which eventually approach a constant.

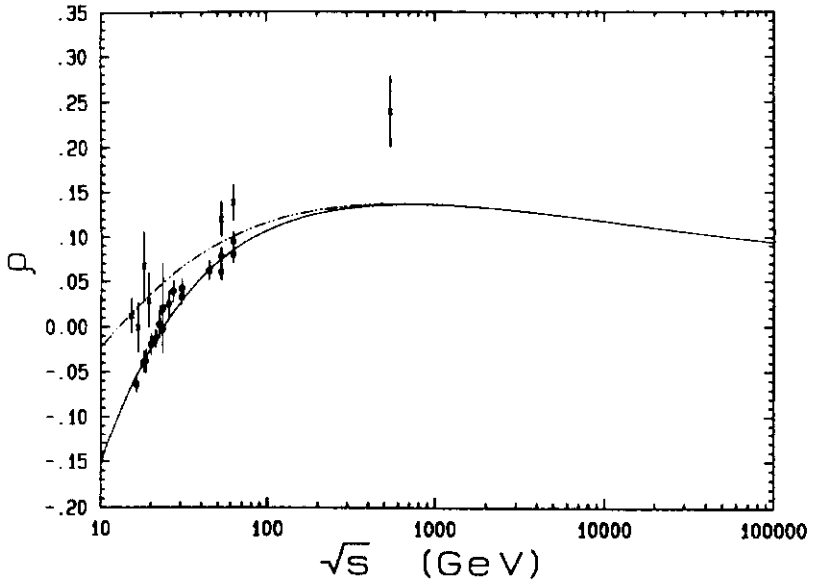

Figure 9. Fits to $\bar{p}p$ and pp values of ρ, from a later version of Reference 10.

The first, and so far only, indication that the simple pictures of hadron-hadron scattering break down is shown in Figure 9. The UA4 measured value[11] of ρ at $\sqrt{s}$ = 546 GeV does not fall on the general fits to all other existing data that worked so well in Figure 8. Although the experimental point is only 2.5 standard deviations from the prediction, many theorists have produced models using this datum point. Since there is then a contradiction between the measured values of ρ and σ_T according to the general model independent fits, the new models have many dramatic features. Examples are given in Figures 10,11,12.

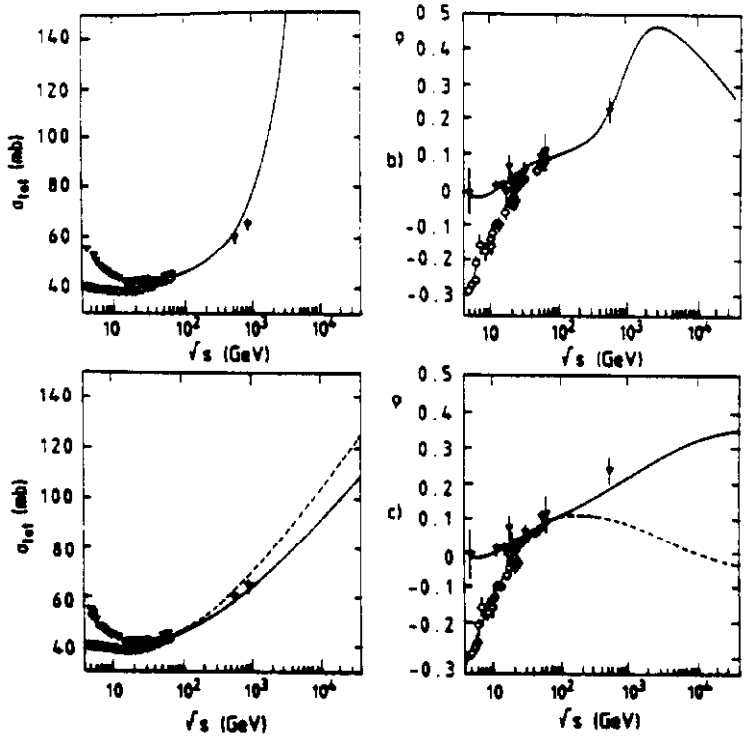

Figure 10. Some predictions for σ_T and ρ for $\bar{p}p$ scattering (solid curves) and pp scattering (dashed curves).

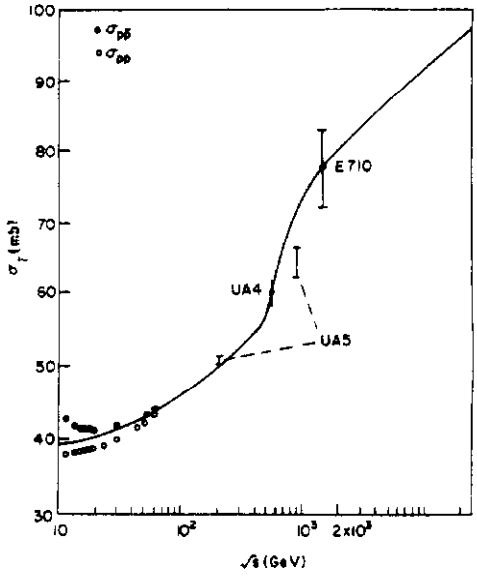

Figure 11. A prediction for σ_T for $\bar{p}p$ scattering; the point marked "E-710" is an early value from this experiment

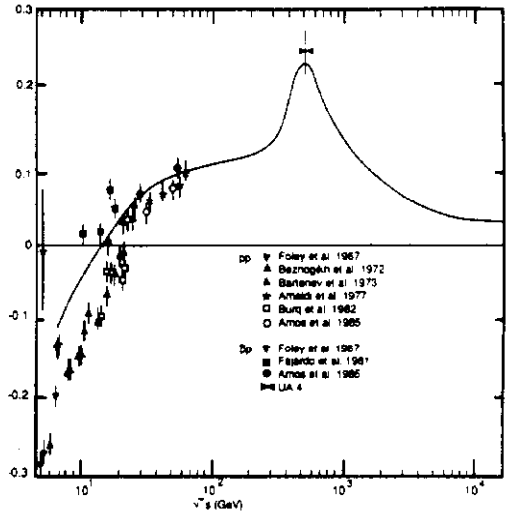

Figure 12. A prediction for ρ for $\bar{p}p$ scattering

Turning now to (single) diffraction dissociation (the process of Figure 2b), Figure 13 shows the experimental distribution[12] of the produced mass M_x; using $x \approx 1 - \frac{M_x^2}{s}$, it falls as $1/M_x^2$ out to $1-x \approx 0.1$. The problem in this reaction is in the experimental definition of diffraction. If the four-momenta of the incoming particles and the outgoing non-dissociated particle are measured, M_x can be obtained, although in order to derive a cross section, the range of integration over M_x must be defined. If these four-momenta are not measured, then indirect methods, open to question, must be used to determine M_x. It is perhaps not too surprising that the resulting experimental situation, Figure 14, shows a confused picture.

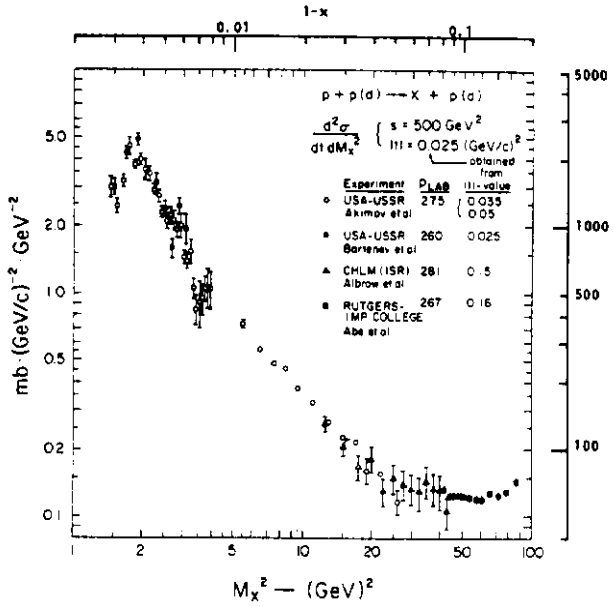

Figure 13. Differential cross section vs. M_x^2 for $pp \rightarrow Xp$ at $|t| = 0.025$ and $\sqrt{s} = 22$ GeV, from Reference 12

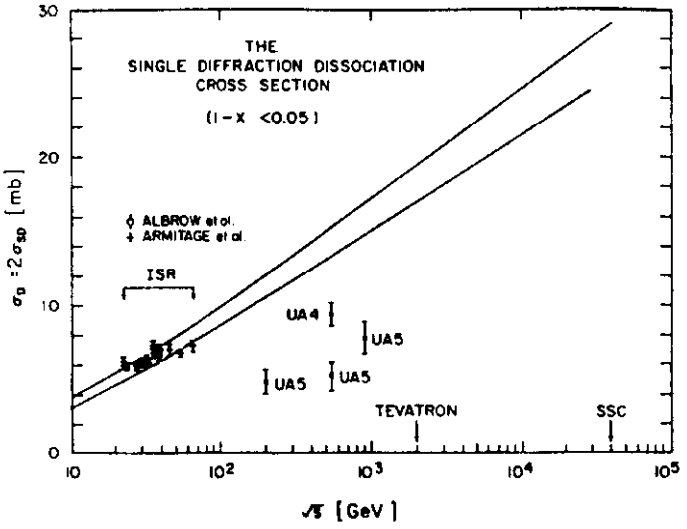

Figure 14. Diffraction dissociation total cross section, from Reference 12

3. <u>E-710</u>

By the late 1980's after UA4 results were available, the open questions were:

(i) What is the energy dependence of σ_T - as s increases, does σ_T go to infinity or to a constant value?

(ii) What is the energy dependence of ρ, and in particular can the UA4 result be confirmed?

(iii) Is the proton becoming blacker as energy increases?

(iv) What is the behavior of B as a function of energy?

(v) What is the behavior of dips in the elastic distribution as a function of energy?

(vi) What is the behavior of diffraction dissociation?

We will give here a progress report on Fermilab E-710, whose goals are to measure σ_T , B, diffraction dissociation and ρ

for $\bar{p}p$ interactions at energies of $\sqrt{s}$ = 300, 546, 1000 and 1800 GeV; data-taking took place in the 1988/89 Tevatron collider run. Data have been analyzed and will be given here on the first 3 topics at 1800 GeV. (13) Other data are currently under analysis. The E-710 personnel are listed in Reference 14.

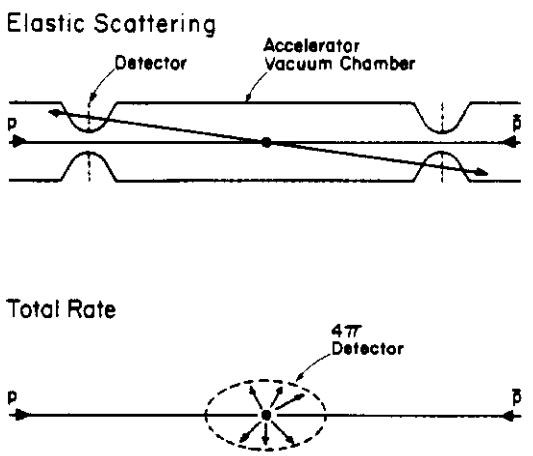

Figure 15. Schematic of hadron collider total cross section and elastic scattering measurement method.

The experimental method used by E-710, similar to that of previous collider experiments at the ISR and SPS, is illustrated in Figure 15. Elastic scattering is measured by detectors in "Roman Pots," which can be moved to very small distances from the circulating beams; at the same time, the total rate is determined using a "4π" detector. A more detailed layout of E-710 is shown in Figure 16.

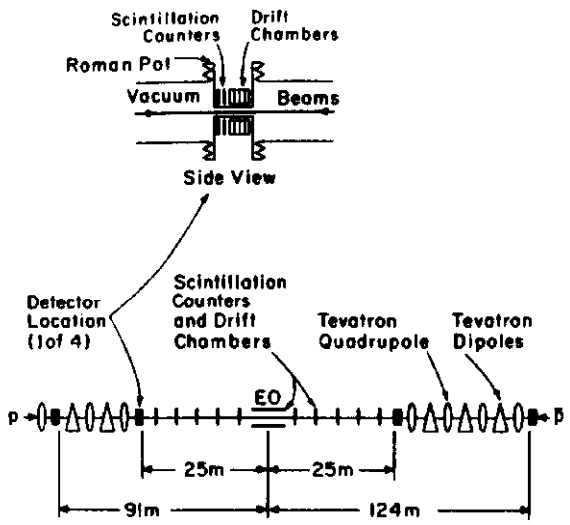

Figure 16. Schematic view of E-710 experiment layout

For elastic scattering we have

$$\frac{dN_{el}}{dt} = L\frac{d\sigma}{dt} \tag{1}$$

where L = integrated luminosity and N is the number of elastic events; using the optical theorem,

$$\left.\frac{dN_{el}}{dt}\right|_{t=o} = L\left.\frac{d\sigma}{dt}\right|_{t=o} = \frac{L(1+\rho^2)\sigma_T^2}{16\pi} \tag{2}$$

For the total rate $\quad N_T = N_{el} + N_{inel} = L\sigma_T \quad (3)$

We have 2 equations, (2) and (3), and two unknowns, L and σ_T, and thus can derive σ_T independently of L; the latter is derived from accelerator parameters, and is currently only known to ~ 15%. [It is possible to normalize elastic scattering to the known

Coulomb cross section to derive σ_T; E-710 will do this later at some energies].

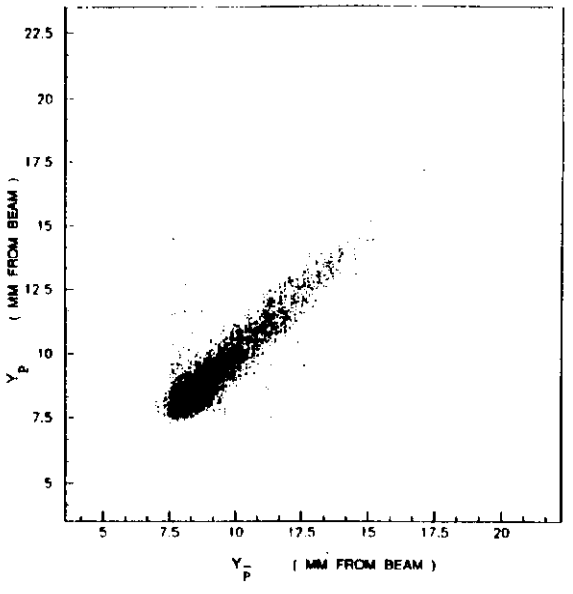

Figure 17. A correlation plot of the vertical (scattering) coordinates of the drift chambers recording the scattered proton and antiproton for each event, for one E-710 run.

From the elastic detectors, scatter plots illustrated by Figure 17 are obtained, showing the elastic correlation between the two outgoing particles from interactions. The main technique that was used to eliminate non-elastic events was to remove those events where an inelastic counter was hit. Remaining backgrounds are generally very low (< few %) in the data analyzed so far. Typical elastic data is illustrated in Figure 18, where 5000 events from one two-hour run are shown. The total number of elastic events obtained in this t range, 50,000, was used to determine N_{el} and σ_{el}.

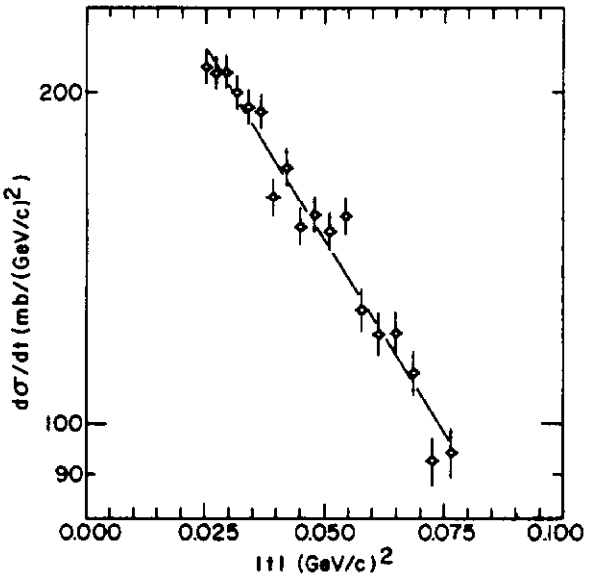

Figure 18. Elastic scattering distribution obtained from one E-710 run

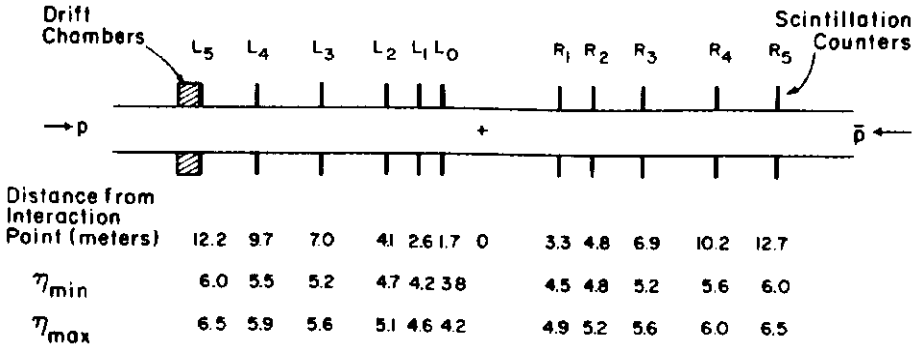

Figure 19. Layout of E-710 inelastic detectors.

Figure 19 shows the layout of the inelastic counters around the Tevatron interaction point. To obtain N_{inel}, we use these ring counters, and correct for their non-4π coverage. LR coincidences (at least one counter on the left of the interaction point and at least one on the right) record 72% of inelastic events, to which are

added single arm events (25%) and extrapolation of single arm events to small angles (2%) and large angles (1%). Single arm events were obtained in special runs with missing bunches of protons and antiprotons, so that beam-gas backgrounds could be determined. The small inelastic drift chambers were also used for this purpose.

Using $\frac{d\sigma}{dt}\,|_{t\,=\,o}$, N_{inel} and N_{el}, σ_T could be derived in a luminosity independent manner as described earlier. This allowed us to derive also the luminosity, which was found to be (1.16 ± 0.10) times the accelerator derived luminosity (the latter is still being studied and more accurate values will eventually be available). To derive the diffraction dissociation cross section, we take the single arm events (with extrapolations), subtract those events (obtained by extrapolation) that would be double arm if there were 4π coverage (30%) and add diffractive events that can give LR events (3%).

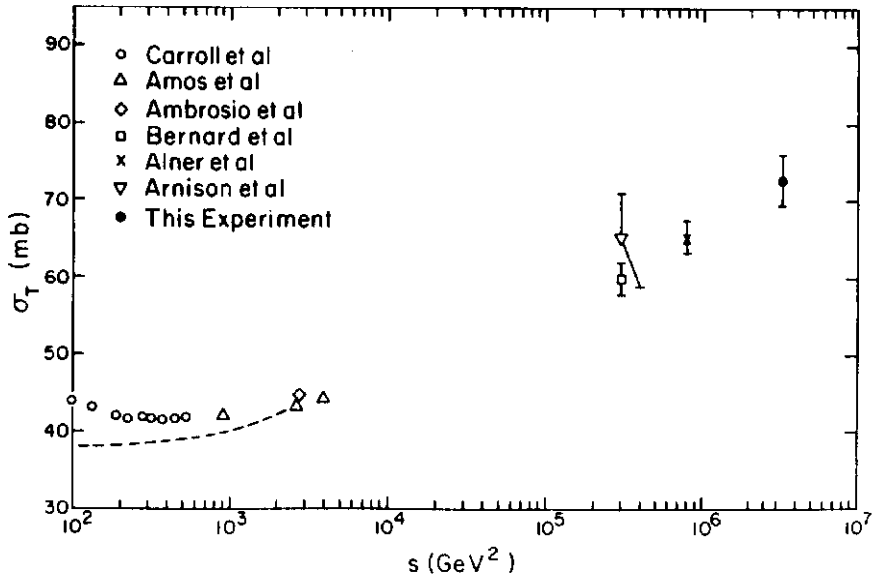

Figure 20. Results for σ_T from E-710 and previous $\bar{p}p$ experiments; the dashed line shows the behavior of the pp total cross section

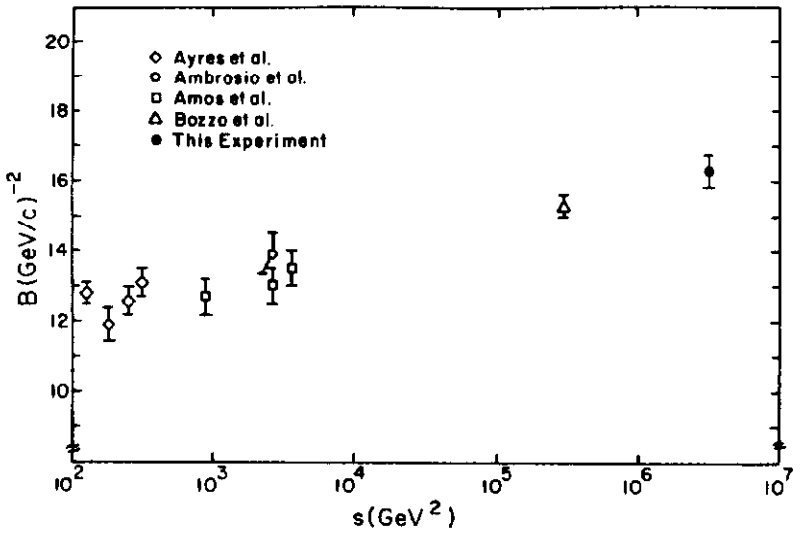

Figure 21. Results for B from E-710 and previous $\bar{p}p$ experiments

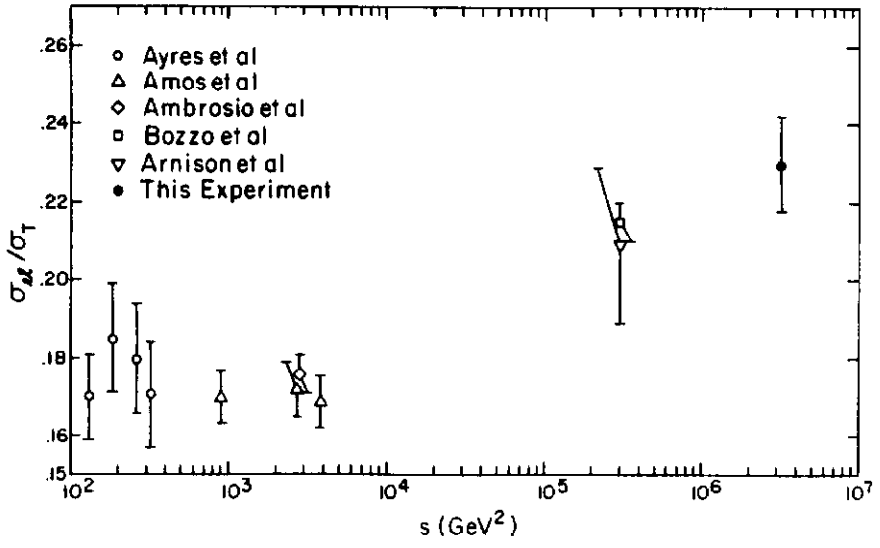

Figure 22. Results for σ_{el}/σ_T from E-710 and previous $\bar{p}p$ experiments

Our results are shown in Figures 20-24, together with earlier data. The total cross section continues to rise, still consistent with $\log^2 s$. Also still rising with increasing s are the values of B and σ_{el}/σ_T ; the increase in the latter quantity shows that the nucleon

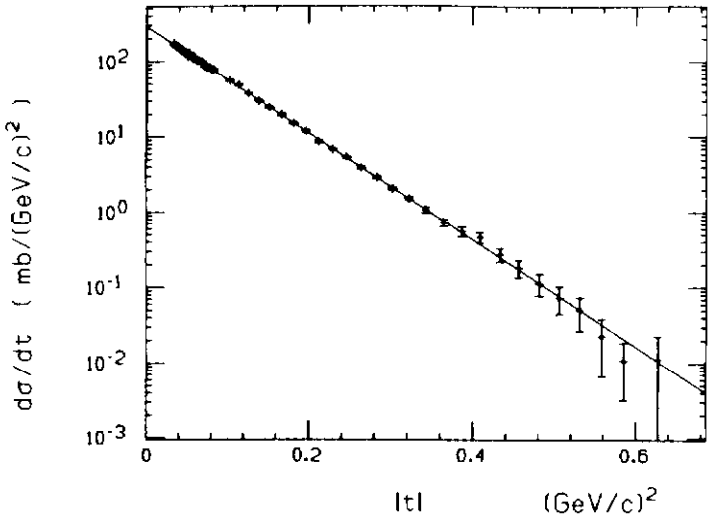

Figure 23. E-710 results for $\frac{d\sigma}{dt}$ at $\sqrt{s}$ = 1.8 TeV from $|t|$ = 0.034 to 0.65

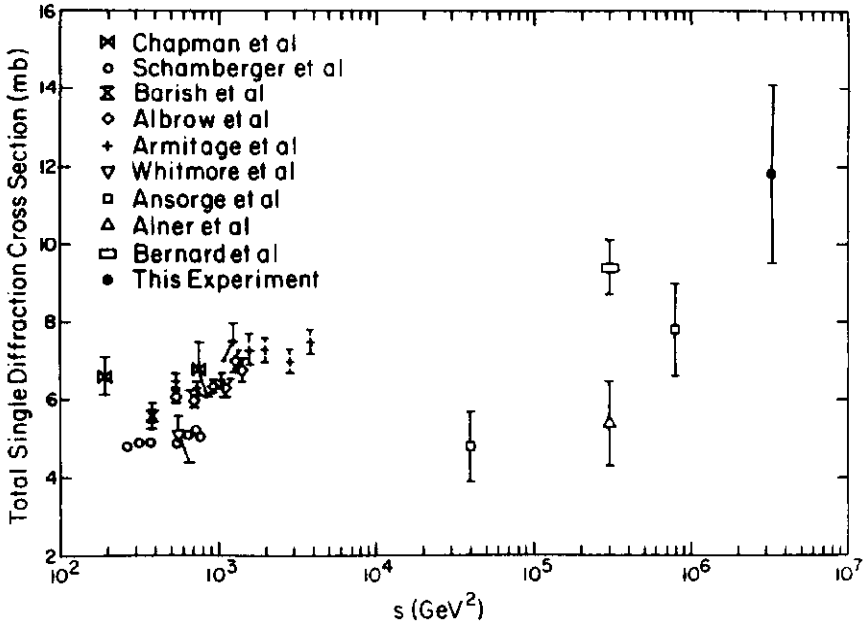

Figure 24. Results for the total single diffraction cross section from E-710 and previous pp and $\bar{p}p$ experiments.

continues to get blacker as energy increases. Figure 23 shows our elastic scattering data at values of $|t|$ out to 0.6; in contrast to the lower energy data of Figure 6, we see that B is constant over the

range $0.034 < |t| < 0.65$.[15] Since at higher energies we expect the distribution to be concave down, as would be obtained from a black disc, our results show that $\sqrt{s} = 1.8$ TeV is the transition energy between these two behaviors. We also see from Figure 23 that there is no dip or break in the distribution out to $t = 0.6$. However, if the simple geometrical relation $(\sigma_T)(t_{dip}) \approx$ constant is valid (see Figure 7), the expected dip or break should be at larger $|t|$ than our data cover. Figure 24 shows our result for diffraction dissociation. As mentioned earlier, the problem here is the differing experimental definitions of diffraction. All that can be said is that the cross section appears to rise with increasing energy.

4. Summary

From all the results presented here, both from E-710 and from lower energy data, the following comments can be made:

1. σ_T continues to rise, consistent with $\log^2 s$. The E-710 data rule out many of the models which have been used to explain the ρ value from UA4.
2. B, σ_{el}, and $\sigma_{diffraction}$ all increase with increasing s.
3. σ_{el}/σ_T increases with s, showing that the nucleon is getting blacker.
4. B is independent of t at $\sqrt{s} = 1.8$ TeV, unlike the situation at lower energies. This is consistent with the nucleon becoming blacker and perhaps eventually becoming like a black disc.

The remaining unanswered questions which we discussed earlier await analysis of E-710 data at energies other than 1800 GeV, and especially values of ρ. In the more distant future we can look forward to data on these processes from the LHC and SSC colliders.

Acknowledgements

The author wishes to thank his colleagues on E-710 for many valuable discussions. The E-710 experiment 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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[1] The units for t are $(GeV/c)^2$ throughout this paper

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Mondardini, J.P. Negret, J. Orear, S.M. Pruss, R. Rubinstein, S. Sadr, J. Sanabria, S. Shukla, M. Spagnoli, I. Veronesi, S. Zucchelli. (Bologna, Cornell, Fermilab, George Mason, Maryland, Northwestern).

[15] Values of B obtained are 16.37 ± 0.45, 16.40 ± 0.12 and 16.30 ± 0.06 $(GeV/c)^{-2}$ for the $|t|$ ranges 0.034 to 0.083, 0.10 to 0.65 and 0.034 to 0.65, respectively.