New results for antiproton-proton elastic scattering and various theoretical models

Fazal-e-Aleem and Mohammad Saleem
Centre for High Energy Physics, Punjab University, Lahore-54590, Pakistan

G. B. Yodh
Department of Physics, University of California–Irvine, Irvine, CA 92717
(Received 16 November 1990)

The most recent measurements of the ratio ρ of the real and imaginary parts of the forward-scattering amplitudes at 0.546 TeV, the total and elastic differential cross sections at 0.546 and 1.8 TeV for proton-antiproton scattering, are compared to the predictions of the generalized Chou-Yang and other theoretical models. For 1.8 TeV, the presence or absence of the break near $-t \approx 0.15$ (GeV/c)^2 and of the dip in the vicinity of 0.6 (GeV/c)^2 are also discussed in the light of various predictions. The possibility of a further rise of the ratio ρ at 1.8 TeV is also probed.

The new results from the Fermilab Tevatron have given a new dimension to antiproton-proton physics. Goals of the Fermilab experiment include the measurements of σ_T, $d\sigma/dt$, B, and the ratio ρ for $p\bar{p}$ interactions at energies of $\sqrt{s}=300$, 546, 1000, and 1800 GeV. The recent results for $p\bar{p}$ elastic scattering at a Tevatron energy of 1.8 TeV, when combined with the measurements at the CERN Collider energy of 546 GeV, impose constraints on theoretical models. This has therefore given rise to some very interesting questions which need to be addressed by the current theoretical models. In order to give a detailed account of these developments we have divided this paper into three sections: namely, (1) introduction and review of new data; (2) review of theoretical models; (3) new results.

I. INTRODUCTION AND REVIEW OF NEW DATA

A. Introduction

The recent unexpectedly high value of the ratio ρ of the real and imaginary parts of the forward-scattering amplitude as measured at 546 GeV (Ref. 1) is an indication of the emergence of new physics at still higher energies. In contradiction to the predictions for the ratio ρ by all the models which explain the CERN ISR and Collider data for $d\sigma/dt$ and σ_T, the ρ was measured to be 0.24 ± 0.04. This unexpectedly high value of ρ suggested a corresponding high value for the total cross section σ_T and thus some new physics around 2 TeV. However the new luminosity-independent measurement of the total cross section at 1.8 TeV (Ref. 2) gives a value of 72.1 ± 3.3 mb in accordance with the $\ln^2 s$ behavior and is consistent with the predictions of most of the models. In fact, all the models which can account for the total-cross-section measurements at 546 GeV and 1.8 TeV do not predict the unexpectedly high value of the ρ at 546 GeV. On the other hand, those models which have attempted to simultaneously account for the total cross section σ_T and the ratio ρ at 546 GeV, predict a total cross section at 1.8 TeV which is higher than the luminosity-independent measurement of σ_T. Very recent measurements of the differential cross section[3] at 1.8 TeV have brought forward further questions. The previous measurements for $d\sigma/dt$ at ISR and Collider energies show a change of slope near $-t=0.15$ (GeV/c)^2. This change of slope disappeared at 1.8 TeV. Another interesting feature of these measurements[3] is that up to $-t\approx0.65$ (GeV/c)^2, it is not clear whether or not a dip has been observed. The models which explain the measurements of $d\sigma/dt$ at 53 and 546 GeV predict a dip in the vicinity of $-t=0.65$ (GeV/c)^2 at 1.8 TeV (the dip moves towards $-t=0$ in these models). It is that the last three points indicate the presence of a dip near $-t=0.65$ (GeV/c)^2? This warrents for very accurate measurements of the differential cross section from $-t=0.6$ to 0.9 (GeV/c)^2. Thus some very fascinating observations are in view and we will try to answer or comment on these questions in light of the predictions of current theoretical models.

B. Review of new data

Among the important additions, to our knowledge, of the experimental data are the recent measurements of the ratio of the real and imaginary parts of the scattering amplitude in the forward direction. Bernard *et al.*[1] reported in 1987 that at $\sqrt{s}=546$ GeV the ratio ρ is 0.24 ± 0.04. This unusually high value was quite unexpected as most of the models were predicting a value around 0.14. While reporting their measurements, they concluded that the measured value of the ratio ρ is definitely higher than the range of values anticipated by the current fits to the data on σ_T and ρ using either dispersion relations or parametrizations with suitable analytical functions of the scattering amplitude.

Recently, Amos *et al.*[4] have reported the results of their measurement on $p\bar{p}$ elastic scattering at the Tevatron Collider at $\sqrt{s}=1.8$ TeV. They have obtained a value of 78.3 ± 5.9 mb for the total cross section σ_T while the nuclear slope parameter B for the elastic scattering was measured to be 16.3 ± 0.5 (GeV/c)$^{-2}$. The latter value was obtained by analyzing the differential cross-

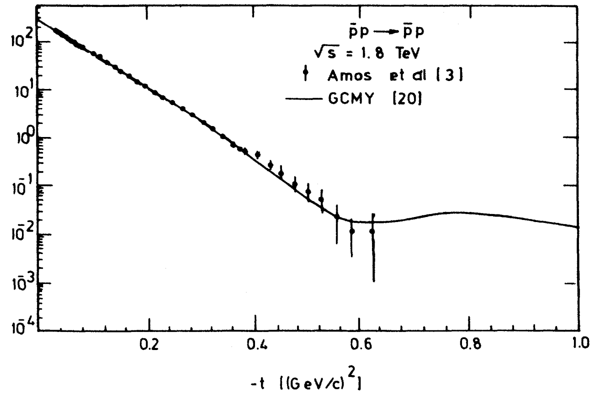

FIG. 1. Differential cross section for $\bar{p}p$ elastic scattering at 1.8 TeV. Solid curve represents predictions of the generalized Chou-Yang model. Experimental points have been taken from Amos *et al.* (Ref. 2).

section data in the range of $0.02 < -t < 0.08$ $(\mathrm{GeV}/c)^2$. They have also measured the integrated cross section by integrating the elastic distribution, using the assumption that B is constant at all t. They obtain $\sigma_{\mathrm{el}} = 19.6 \pm 3.0$ and a ratio $\sigma_{\mathrm{el}}/\sigma_T = 0.25 \pm 0.02$.

Very recently, Amos *et al.*[2] have also given the luminosity-independent measurements of $p\bar{p}$ total cross sections at 1.8 GeV. Their results give $\sigma_T(1+\rho^2)^{1/2} = 72.9 \pm 3.3$ mb. By assuming $\rho = 0.145$, the total cross section is obtained as 72.1 ± 3.3 mb. A value of $\rho = 0.24$ leads to $\sigma_T = 69.6 \pm 3.2$ mb. They also derived the elastic cross section $\sigma_{\mathrm{el}} = 16.6 \pm 1.6$ mb while the ratio of elastic and total cross sections, $\sigma_{\mathrm{el}}/\sigma_T$, is given as 0.230 ± 0.012. These values though generally lower than their earlier measurements, are within errors consistent with them.[1]

The latest additions to the experimental data on proton-antiproton elastic scattering at 1.8 TeV are the measurements of the differential cross section by Amos *et al.*[3] They report the differential cross-section data covering the t range $0.034 \leq -t \leq 0.65$ $(\mathrm{GeV}/c)^2$. Results of their measurements are given in Fig. 1. In this range, the differential cross section appears to fall exponentially. However, because of large error bar(s) there is an indication of a shallow dip or a shoulder in the vicinity of 0.6 $(\mathrm{GeV}/c)^2$. Only the precise measurements around and beyond this value will be able to determine the presence or the absence of a dip. The slope parameter is given as 16.3 ± 0.3 $(\mathrm{GeV}/c)^{-2}$. This is in contrast with the situation at lower energies where a change of slope is observed at $-t \approx 0.15$ $(\mathrm{GeV}/c)^2$.

II. REVIEW OF THEORETICAL MODELS

Let us now briefly discuss the current attempts to explain these results theoretically, by using also the QCD-based phenomenology. In the process of doing so we will first consider those models which try to account for the ratio ρ and the total cross section σ_T at ISR, Collider, and Tevatron energies. We will then include the fitting of the differential cross section at these energies.

Immediately after the publication of the result on ρ $(=0.24 \pm 0.04)$ at 546 GeV, Bernard *et al.*[5] showed that the data on the total cross section σ_T and the ratio ρ from $5 < \sqrt{s} < 540$ GeV including the measurement of ρ at 540 GeV could be well described by the presence of the odderon in the crossing-odd amplitude. If the unexpected phenomena such as the opening of a new threshold were excluded, this high value of ρ at 546 GeV was shown to be incompatible with the neglect of the odd-under-crossing amplitude. Their prediction of the total cross section for $p\bar{p}$ scattering at $\sqrt{s} = 1.8$ TeV is consistent with the most recent measurements at Tevatron Collider. However, Breedon *et al.*[6] have recently shown in their precise measurements that their value of $\Delta\rho = \rho(p\bar{p}) - \rho(pp) = 0.031 \pm 0.010$ at $\sqrt{s} = 24.3$ GeV disagrees with the odderon fit of Bernard *et al.*[5] which yields a value of 0.061, much higher than the measured value.

Leader[7] has analyzed the consequences of the rapid growth in ρ at $\sqrt{s} = 546$ GeV. He has pointed out that rise in the ratio ρ is even more dramatic when translated into the behavior of the real part of the scattering amplitude. In order to account for this growth, with $\sigma_T(pp) - \sigma_T(p\bar{p}) = 0$, a considerably larger value of σ_T (of the order of 85–95 mb) than that expected from the usual extrapolation value of σ_T is predicted at 1.8 TeV. Alternatively, if the total cross section is 75 mb at the Fermilab Tevatron it is inferred that $\sigma(pp) - \sigma(p\bar{p}) \approx 4 - 10$ mb. Recent measurements at the Tevatron seem to support the second conclusion. This conclusion is also consistent with the predictions of Bernard *et al.*[5] However, a conclusive remark can be made only after the measurements at Tevatron for $p\bar{p}$ scattering are compared with similar measurements for pp scattering. It is finally speculated by Leader that this unexpectedly large value of ρ is indicating the presence of the threshold of new physics.

In 1988, Kluit and Timmermans[8] gave an analysis of σ_T and ρ including the UA4 results of the ratio of the real and imaginary part of the scattering amplitude, based on dispersion relations which are essentially based on one axiom (which is the foundation for all models of elastic scattering), the analyticity of the forward elastic scattering amplitude. Dispersion relations can only be derived if a certain asymptotic behavior of the forward elastic scattering amplitude is assumed. Their interpretation is twofold. They deduce a steep rise of the total cross section in the 1–4 TeV domain if $p\bar{p}$ and pp cross sections are asymptotically identical. Fitting the data for σ_T and ρ at the Collider, they predict a total cross section between 79 and 101 mb at 1.8 TeV. This is above the measured value at this energy. However, if $p\bar{p}$ and pp total cross sections are different, they deduce a crossing of the σ_T between ISR and CERN SPS energies followed by a steep rise of the difference of the $p\bar{p}$ and pp cross sections. Their predictions again are significantly above the measured values. These authors have also pointed out that in both cases the rise can be interpreted as the threshold of a new process.

Block and Cahn[9] gave a parameterization that manifests the proper analyticity for the forward scattering amplitude. In their model, the scattering amplitudes for pp and $p\bar{p}$ were expressed in terms of even and odd amplitudes. By choosing some of the parameters as energy dependent they have calculated σ_T and ρ. Their fits explain the data well except for ρ at $\sqrt{s}=546$ GeV. Saleem and Aleem[10] have used similar expressions for the scattering amplitudes for pp and $\bar{p}p$ elastic scattering as in Ref. 9 with different parameters. Their fit to the entire data for σ_T and ρ for pp and $\bar{p}p$ elastic scattering at ISR, Collider, and cosmic-ray energies is good. The parameterization depicts $\ln^2 s$ behavior and its predictions at 1.8 TeV yields $\sigma_T=80$ mb. This value is in agreement with the earlier measurements of Amos *et al.*[4] while it is higher than the recent measurements of Amos *et al.*[2]

Let us now consider those models which also take into account the fitting of the differential cross section.

A. Regge models

Aleem and Saleen[11] have used a Regge-pole-plus-cut model to explain the data at 546 and 630 GeV. At these energies, the model gives a satisfactory explanation of the total cross section σ_T, the ratio σ_{el}/σ_T, the slope B in the range $0 \le t < 0.15$ (GeV/c)^2 and the differential cross section up to $-t \approx 2.2$ (GeV/c)^2. However, it predicts a value of 0.167 for the ratio ρ which is lower than the measured value. At 1.8 TeV, the values of σ_T, σ_{el}/σ_T, B, and ρ are predicted to be 74.8 mb, 0.25, 15.9, (GeV/c)$^{-2}$, and 0.174, respectively. The model thus predicts correct values of the total cross section, the ratio of the elastic and total cross sections, and the slope parameter at the most recent measurements at the Tevatron. The predictions of this model for the differential cross section are given in Fig. 2. The theoretical curve is in good agreement with the data.[3] However, unlike the eikonal models, the Regge model predicts a shoulder near $-t=0.8$ (GeV/c)^2. The model also successfully accounts for the disappearance of the break near $-t=0.15$ (GeV/c)^2 which is observed at ISR and Collider energies. This is due to the fact that the Pomeron contribution becomes insignificant at 1.8 TeV and the major contribution comes from the $\mathbb{P}\otimes\mathbb{P}$ cut. It is interesting to point out that recently Kopeliovich *et al.*[12] have given a QCD-based phenomenological description of the rising total cross sections from ISR to cosmic-ray energies. They predict the value of σ_T at 1.8 TeV to be 85–95 mb, which is considerably higher than the recent measurements. But they have also plotted the variation of the total cross section with the intercept Δ of the QCD Pomeron at 1.8 TeV. It may be noticed from Fig. 3 that the value of Δ which is consistent with the current measurements of the total cross section σ_T at Tevatron energy $\sqrt{s}=1.8$ TeV is the same as that for the conventional Pomeron.

In their recent analysis of $p(\bar{p})p$ elastic scattering, Jankovszky *et al.*[13] have introduced a vacuum singularity with negative C parity and a high intercept $\alpha(0)\approx 1$ into the scattering amplitude. They have given a good description of the most of the available data at ISR and Collider energies. However, the model does not give correct results for $-t > 5$ (GeV/c)^2 at ISR energies. Also

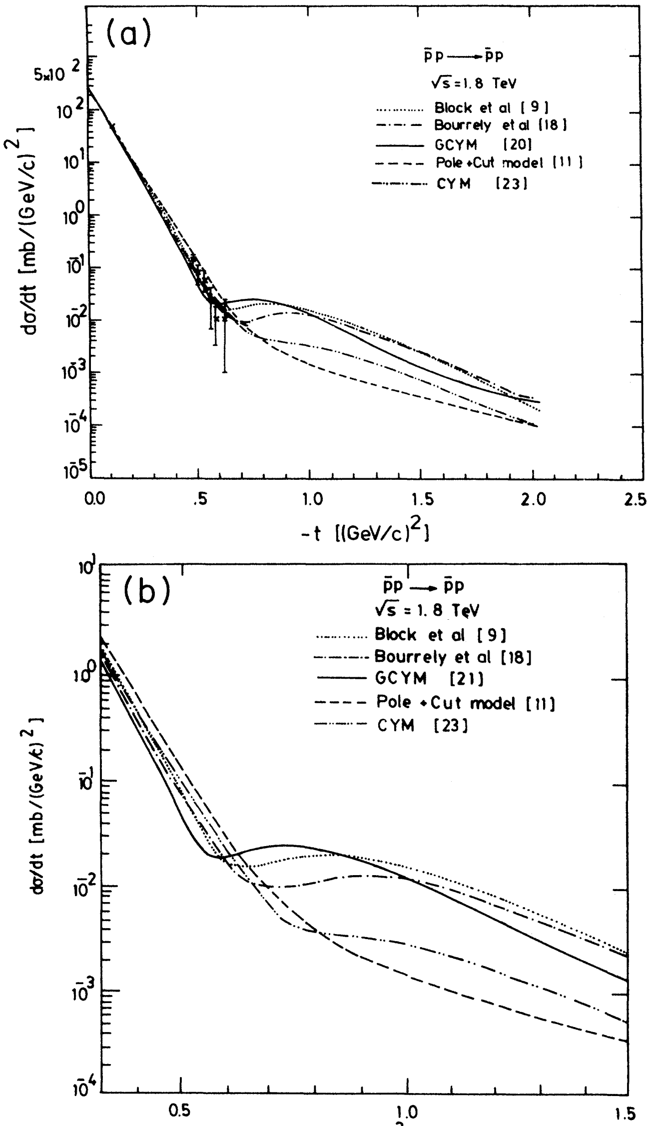

FIG. 2. (a) and (b) Differential cross section for $\bar{p}p$ elastic scattering at 1.8 TeV plotted against predictions of various models (Refs. 9, 11, 18, 20, and 23). Only the representative data from Amos *et al.* (Ref. 2) is plotted.

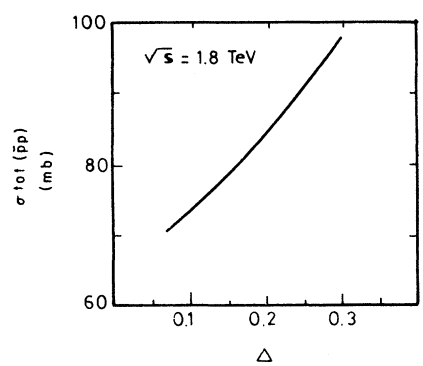

FIG. 3. Intercept of the QCD Pomeron as predicted in Ref. 12 vs the $\bar{p}p$ total cross section.

the prediction of the model that $\rho=0.136$ at 546 GeV is much smaller than the measured value. Their predictions for the differential cross section at 1.8 TeV are consistent with the recent measurements.[4] They have also given the predictions of their model at 2.2 TeV. As seen from the Fig. 8 of Ref. 13, the model predicts a dip around $-t=0.75$ (GeV/c)^2. As their model predicts the movement of the dip towards $t=0$, the dip at 1.8 TeV will appear beyond $-t=0.75$ (GeV/c)^2. They finally conclude that the presence of the odderon is suggested by QCD and by their fit. They stress that from the perturbative QCD point of view, the odderon is more convenient object to study than the Pomeron.

B. QCD-based eikonal models

Very recently, Durand and Pi[14] have given an analysis of high-energy $\bar{p}p$ and pp elastic scattering based on a model in which the energy dependence of very-high-energy processes is driven by semihard scattering of quarks and gluons in the nucleons. This is a good addition to the models[15] which incorporate semihard parton-parton scattering. These models, however, differ mostly in their treatment of QCD and also whether or not they respect the constraints imposed by unitarity. The common feature of these models is that they associate the growth in the $\bar{p}p$ and pp total cross sections with the increase in the gluon distribution functions at small x of the momentum of the nucleon carried by the parton. They demonstrate that the parton-parton distribution not only gives the observed increase in total, inelastic, and elastic scattering in the forward direction, but also, through analyticity, give a rapid increase of ρ with energy giving a high value of this parameter at $\sqrt{s}=546$ GeV. Working in the impact-parameter representation and neglecting the spin, they have fitted the data for the differential cross section at 546 GeV. The predictions of their model are excellent in the diffraction-peak region. However, as shown in Fig. 4, these predictions are not consistent with the experimental data in the dip region and beyond. They also note that the smearing out of the gluon or parton distribution relative to the soft valance-quark distribution is quite important in getting a good fit in the forward-scattering region of the differential cross section. Their prediction at 1.8 TeV for the total cross section is also higher than the measurement by Amos *et al.*[4] They have not given the predictions for σ_{el}/σ_T and $d\sigma/dt$ at Tevatron energy and for $d\sigma/dt$ at ISR energies.

Margolis *et al.*[16] have recently claimed that the remarkably high value of ρ at 546 GeV does not suggest the onset of new physics, i.e., the introduction of new particles, but is rather a natural feature of QCD in this energy range. This is due to the rapid increase of the gluon content inside hadrons with an increase in energy. Hadronic interactions therefore become semihard near 1 TeV and can be calculated by using the perturbative QCD. This production of the gluons near 1 TeV has been associated with the discovery of "minijet phenomena" at the UA1 and similar indication of jetlike structure at certain cosmic-ray measurements. Using QCD-inspired phenomenology, they have given a good description of the ratio ρ and the slope parameter B. However, their result is higher than the most recently measured total cross section at 1.8 TeV.

Block *et al.*[17] very recently extended the earlier work of Ref. 16 so as to include predictions at 1.8 TeV. They have pointed out that in their model the production of gluon jets becomes a feature of average hadron collision for multi-TeV energies where interactions are mostly mediated by semihard gluons. Fitting the entire total-cross-section data including Fermilab Tevatron results they deduce that ρ at 546 is ≈ 0.14, well below the measured value of 0.24, thus claiming this number as a critical issue. They have given the predictions of their model at 1.8 TeV. These results are also plotted in Fig. 2 together with the most recent measurements at 1.8 TeV.[3] As can be seen from Fig. 2, the agreement is good up to $-t\approx 0.65$ (GeV/c)^2. According to the predictions of their model a dip and bump structure should be observed in the vicinity of $-t\approx 0.65$ (GeV/c)^2. Extension in the measurements of Fermilab Tevatron to the larger $-t$ values will enable us to test their predictions.

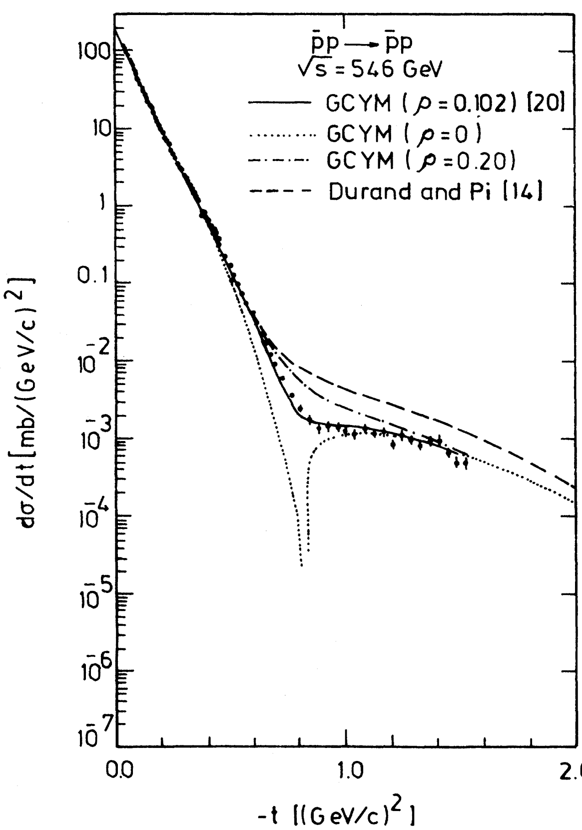

FIG. 4. Differential cross section for $\bar{p}p$ elastic scattering at 546 GeV. Solid, dotted, and dash-dotted curves represent the predictions of the generalized Chou-Yang model for different values of α. The dashed curve is the prediction of Durand and Pi (Ref. 14). Experimental points have been taken from Bozzo *et al.* (Ref. 26).

C. Eikonal models

The eikonal picture which has theoretical foundations in some areas of physics has been successful in explaining the various aspects of elastic scattering at high energies. Chou and Yang[18] first proposed a preliminary version of eikonal model for hadron-hadron elastic scattering. The model is based on geometrical considerations in which hadrons are treated as extended objects. Survey of literature shows[15] that it has been successful only in the diffraction-peak region. In order to explain the experimental data beyond the diffraction-peak region, Glauber and Velasco[19] generalized the Chou-Yang model. An expression is obtained for the scattering amplitude in this model which is based on the multiple diffraction theory. This model, which reduces to the Chou-Yang model[18] when the interactions are considered to be purely absorptive, gave very good results at 546 GeV. However the model does not give good results at ISR energies. In order to explain $p(\bar{p})p$ elastic scattering, by using a parameterization of the proton form factor $G(t)$ which is consistent with the experiment and by taking into account the anisotropy of the scattering in a simple form, Saleem *et al.*[20] obtained very good agreement with the experimental data at ISR and Collider energies. Using the same expressions as in Ref. 20, Aleem *et al.*[21] predicted the differential cross-section results corresponding to the total cross-section value of 79.91 mb. The predictions of the model are consistent with the then available measurements of Amos *et al.*[4]

Bourrely *et al.*[22] have recently given an update of their model which is based on the eikonal picture. With the improvement in the accuracy of the experimental data at collider energies, they have slightly modified the six parameters used in the pristine version of the model. Assuming that the Regge contribution is negligible at energies of 546 GeV and higher, they have compared the results of their model with the experimental data at Collider energies $\sqrt{s}=546$ and 630 GeV, which are in excellent agreement near the forward direction. However in the dip region and beyond, the theoretical curve overestimates the values of the differential cross section. Also, the model does not account for the very high value of the ρ at $\sqrt{s}=546$ GeV. They have also given the predictions of the model at $\sqrt{s}=1.8$ TeV where the measurements have recently been made. Their model gives correct results for the total cross section, ratio of the elastic to total cross section, and the slope parameter at 1.8 TeV. Predictions of the model for the differential cross section at 1.8 TeV are also in good agreement with the experimental measurements.[3] The dip is predicted at 0.7 $(\text{GeV}/c)^2$. It may be further pointed out that their choice of the scattering amplitude at high energies is such that the predictions of the model are the same for both pp and $p\bar{p}$ elastic scattering at the Collider and the Tevatron energies, thus ruling out the presence of an "odderon" at these energies.

III. NEW RESULTS

A. Predictions of generalized Chou-Yang model

Let us now compare the predictions of the generalized Chou-Yang model[20] with the new results at 546 and 1800 GeV. According to the generalized Chou-Yang model, hadrons consist of clusters of particles which, on collision, pass through each other, interacting in pairs i,j and scattering one another with invariant scattering amplitudes $f_{ij}(t)$. The scattering amplitude $T(s,t)$ is then given by

$$T(s,t)=-i\int bJ_0(b\sqrt{-t})\{1-\exp[-\Omega(s,b)]\}db ,$$

where

$$\Omega(s,b)=K(1-i\alpha)\int \sqrt{-t}\,d\sqrt{-t}\,J_0(b\sqrt{-t})[f(t)/f(0)]G_A(t)G_B(t) .$$

The function $\Omega(s,b)$ represents principally an opacity effective for clusters passing with a relative impact parameter b, but is taken to be complex and thereby includes refractive as well as absorptive effects. $f(t)/f(0)$ is an unknown function which is supposed to take account of the anisotropy of the parton-parton interaction. The parameter α is determined by the ratio of the real and imaginary parts of the scattering amplitude in the forward direction. $G_A(t)$ and $G_B(t)$ are form factors of colliding particles. The parameter K is adjusted so that the experimental value of total cross section is obtained. It is interesting to note that when the scattering of constituent partons is isotropic so that $f(t)/f(0)$ is equal to unity and the interactions are considered to be purely absorptive so that $\alpha=0$, then the model based on the multiple-diffraction theory reduces to that of Chou and Yang,[18] involving only the imaginary part of the scattering amplitude. For $p(\bar{p})p$ elastic scattering, $G_A(t)=G_B(t)=G(t)$. Using the following parameters as given in Ref. 20 for the proton form factor and the anisotropy function,

$$G(t)=0.6405\exp(4t)+0.33\exp(0.85t)+0.028\exp(0.22t)+0.0015\exp(0.05t) ,$$

and

$$f(t)/f(0)=(1+At)/(1-At)^{(n)} ,$$

where $n=\frac{1}{3}$ $(\text{GeV}/c)^{-2}$ and $A=\frac{1}{3}$ $(\text{GeV}/c)^{-2}$, we have calculated the differential cross section at 546 and 1800 GeV. The results of our calculations at 546 GeV are shown in Fig. 4. As shown in the figure, the model gives excellent agreement with the experimental measurements of the differential cross section when we choose $K=16.9$ $(\text{GeV}/c)^{-2}$ and $\alpha=0.14$ which yields $\rho=0.102$ (solid curve). This value of ρ is in disagreement with the recent measurements of Bernard *et al.*[1] If we choose $K=15.95$

$(\text{GeV}/c)^{-2}$ and $\alpha=0.275$, we obtain the correct value of σ_T and ρ at 546 GeV. However, we observe that the differential cross-section results exceed the experimental measurements (dash-dotted curve). Similar results are obtained by Durand and Pi[14] (dashed curve) and Bourrely *et al.*[22] in an attempt to fit the most recent measurements of ρ. The differential cross section corresponding to $\rho=0$ is also plotted in Fig. 4. This depicts the behavior of the imaginary part of the scattering amplitude. Figure 1 exhibits the predictions of our model for the differential cross-section curve at 1.8 TeV corresponding to the total cross section equal to 76.23 mb. The value of K required to yield the corresponding experimental value of σ_T is 23.5 $(\text{GeV}/c)^{-2}$. The curve in Fig. 1 shows that with the experimental measurements yielding this value of the total cross section, the dip in the differential cross section is exhibited at $-t=0.58$ $(\text{GeV}/c)^2$. This curve is obtained by choosing $\alpha=0.18$ which yields $\rho=0.118$. These predictions are consistent with the new measurements as the errors in the measurements of the differential cross sections accommodate the dip at $-t=0.58$ $(\text{GeV}/c)^2$. However, this dip may transform into a shoulder due to the higher contribution of the real part of the scattering amplitude in the dip region. The calculated differential cross section begins to fall again at $-t\approx 0.73$ $(\text{GeV}/c)^2$. The differential cross section at the dip and bump is 1.68×10^{-2} mb/$(\text{GeV}/c)^2$ and 2.2×10^{-2} mb/$(\text{GeV}/c)^2$, respectively. The slope parameters at $-t=0.11$ $(\text{GeV}/c)^2$ is 15.89 $(\text{GeV}/c)^{-2}$ which is consistent with the experimental value of 16.3 ± 0.5 $(\text{GeV}/c)^{-2}$. The ratio of the integrand to the total cross section, $\sigma_{\text{el}}/\sigma_T$, is 0.25 and is consistent with the experimental measurement made in Ref. 4.

Very recently Chou-Yang[23] have proposed that the assumption regarding the equivalence of the charge form factor is only an approximation within the framework of the geometrical picture.[15,18,24] They have thus given a simple expression for the proton matter distribution. A similar assumption was made by Saleem *et al.*[25] in explaining the $\bar{p}p$, $p\alpha$ and $\alpha\alpha$ elastic scattering. However, unlike the assumption made in Ref. 25, Chou and Yang have taken the hadronic form-factor energy dependent. By choosing an energy-dependent range parameter, they have fitted the $p(\bar{p})p$ elastic scattering data at 23.5 and 546 GeV. Their fit to the data at 23.5 GeV is good up to $-t\approx3.0$ $(\text{GeV}/c)^2$. Beyond this value of $-t$ the deviation from the experimental data becomes significant as the $-t$ value increases. They have also given a good fit to the data at 546 GeV. By assuming that two parameters used to fit the data at ISR and Collider energies as increasing linearly with ln$s$ and taking the ratio ρ at Tevatron as 0.24, they have predicted the differential cross section at 1.8 TeV. These predictions are plotted in Fig. 3 along with the experimental results. These predictions are in good agreement with the experiment. They predict a shoulder near $-t=0.75$ $(\text{GeV}/c)^2$. They finally remark that if their proposed hadronic form factor is approximately correct, the $p(\bar{p})p$ system would become increasingly more opaque and the region of opaqueness expands as the energy increases. They have also pointed out that the multiple dip structure continues to be a feature of their model. This multiple dip structure is inconsistent with the ISR energies where at $\sqrt{s}=53$ GeV a second dip has been observed up to $-t\approx10$ $(\text{GeV}/c)^2$.

B. Remarks

The following observations have been made.

(i) Luminosity-independent measurements of the total cross section at 1.8 TeV are consistent with the predictions of the conventional models. These measurements are also consistent with the $\ln^2 s$ behavior. However, the conventional models are unable to account for the unexpected rise of ρ at $\sqrt{s}=546$ GeV. Is this measurement of ρ at 546 GeV a critical issue as pointed by Block *et al?*[9] A measurement of ρ at 1.8 TeV might throw more light on this issue.

(ii) A change of slope near $-t\approx0.15$ $(\text{GeV}/c)^2$ was observed at ISR and Collider energies. This has disappeared at the Tevatron energy of 1.8 TeV. In the Regge framework this can be explained by the diminishing contribution of the Pomeron at 1.8 TeV. In the eikonal models we do not get information about this parameter from the published work.

(iii) The dip and/or shoulder observed at ISR and Collider energies has not been clearly observed up to $-t\approx0.65$ $(\text{GeV}/c)^2$ although the last three points of the measurements can accommodate a dip in the vicinity of $-t=0.6$ $(\text{GeV}/c)^2$ as predicted by the generalized Chou-Yang model. Thus there is a need for very precise measurements of the differential cross section in the vicinity of 0.65 $(\text{GeV}/c)^2$. All other models which explain the measured data at ISR and Collider energies also predict a dip between 0.65 and 0.85 $(\text{GeV}/c)^2$. In the eikonal models[9,18] this dip is predicted between 0.65 and 0.75 $(\text{GeV}/c)^2$ and its movement towards $-t=0$ continues. In the dipole Pomeron model the movement of the dip towards $-t=0$ is slower. In the Regge model[11] this dip is predicted at $-t=0.8$ $(\text{GeV}/c)^2$ and it does not further move towards $-t=0$ as the major contribution to the scattering amplitude is coming from the $\mathbb{P}\otimes\mathbb{P}$ cut.

(iv) The predictions of the generalized Chou-Yang model suggest that if the ratio ρ is still increasing at Tevatron energies, then the dip will be transformed into a shoulder or break as the increasing contribution of ρ will fill the dip.

(v) Are the Tevatron energies suggesting the onset of a new physical phenomena as pointed out by Bernard *et al.*[5] and Leader *et al.*?[7] Measurement of ρ at 1.8 TeV will throw more light on this phenomenon. If the value of this parameter is comparable to 0.24 (measured value of ρ at 546 GeV), then the models will need radical modifications.

Thus the new measurements at the Tevatron in the vicinity of and beyond $-t=0.60$ $(\text{GeV}/c)^2$ will be very interesting and will give us an opportunity to test the validity of various models.

[1]D. Bernard, *et al.*, Phys. Lett. B **198**, 583 (1987).
[2]N. A. Amos *et al.*, Phys. Lett. B **243**, 158 (1990).
[3]N. A. Amos *et al.*, Phys. Lett. B **243**, 158 (1990).
[4]N. A. Amos *et al.*, Phys. Rev. Lett. **63**, 2784 (1989).
[5]D. Bernard *et al.*, Phys. Lett. B **199**, 125 (1987).
[6]R. E. Breedon *et al.*, Phys. Lett. B **216**, 459 (1989).
[7]E. Leader, Phys. Rev. Lett. **59**, 1525 (1987).
[8]P. M. Kluit and J. Timmermans, Phys. Lett. B **202**, 458 (1988).
[9]M. M. Block and R. N. Cahn, Phys. Lett. B **188**, 143 (1987).
[10]Mohammad Saleem *et al.*, in *Proceedings of the 21 International Cosmic Ray Conference,* Adelaide, Australia, 1990, edited by R. J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 6, p. 43.
[11]Fazal-e-Aleem and M. Saleem, Pramana **31**, 99 (1988).
[12]B. Z. Kopeliovich *et al.*, Phys. Rev. D **39**, 769 (1988).
[13]L. L. Jenkovszky *et al.*, Z. Phys. C **36**, 495 (1987); Yad. Fiz. **46**, 1200 (1987) [Sov. J. Nucl. Phys. **46**, 700 (1987)]; Pis'ma Zh. Eksp. Teor. Fiz. **47**, 288 (1988) [JETP Lett. **47**, 346 (1988)].
[14]L. Durand and H. Pi Phys. Rev. D **40**, 1436 (1989).
[15]Fazal-e-Aleem and M. Saleem, *Chou-Yang Model and Elastic Reactions at High Energies* (Hadronic, Florida, in press).
[16]B. Margolis *et al.*, Phys. Lett. B **213**, 221 (1988).
[17]M. M. Block *et al.*, Phys. Rev. D **41**, 978 (1990).
[18]T. T. Chou and C. N. Yang, Phys. Rev. **170**, 1591 (1968); Phys. Rev. Lett. **20**, 1213 (1968); L. Durand and R. Lipes, *ibid.* **20**, 637 (1968).
[19]R. J. Glauber and J. Velasco, Phys. Rev. Lett. B **147**, 380 (1984).
[20]Mohammad Saleem *et al.*, Europhys. Lett. **6**, 201 (1988).
[21]Fazal-e-Aleem *et al.*, J. Phys. G **16**, L269 (1990).
[22]C. Bourrely *et al.*, Nucl. Phys. **B247**, 15 (1984); Z. Phys. C **37**, 369 (1988).
[23]T. T. Chou and C. N. Yang, Phys. Lett. B **244**, 113 (1990).
[24]S. Y. Lo, in *Geometrical Picture in Hadronic Collisions* (World Scientific, Singapore, 1987).
[25]Mohammad Saleem *et al.*, Europhys. Lett. **3**, 539 (1987).
[26]M. Bozzo *et al.*, Phys. Lett. **155B**, 197 (1985).