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Elastic $p\bar{p}$ and pp scattering up to $\sqrt{s}=546$ GeV and the flavored perturbative Reggeon field theory

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We show that the *perturbative* Reggeon field theory (RFT), with flavoring corrections added, reproduces the pp and $p\bar{p}$ differential cross sections from Fermilab to the CERN SPS collider ($Sp\bar{p}S$). This completes a long program of phenomenology which is now capable of providing a unified framework for soft hadronic scattering at current energies. Our scenario of data being influenced by finite scales at least up to $\sqrt{s}=546$ GeV is compatible with the truly *asymptotic* limit being described by the *critical* RFT scaling laws.

INTRODUCTION

It has become clear that even at the CERN SPS collider ($Sp\bar{p}S$), soft hadron scattering is not described by any simple asymptotic behavior. Instead, large nonleading terms associated with large energy scales dominate the dynamics. For example, consider the simple "logarithm-squared-s" form for the average pp, $p\bar{p}$ total cross section which has often been used,[1]

$$\sigma_{\rm tot}=A\left[1+g_0\ln^2\left(\frac{s}{s^*}\right)\right] . \qquad (1)$$

A recent fit[1(a)] yields the scale $s^*=243.6\ \text{GeV}^2$, much larger than $s_0=1\ \text{GeV}^2$. This scale is crucial. To see the importance of s^*, decompose Eq. (1) in powers of $\ln(s/s_0)$ as

$$\sigma_{\rm tot}=A_2\ln^2(s/s_0)-A_1\ln(s/s_0)+A_0$$
$$=\sigma_2-\sigma_1+\sigma_0 .$$

Using[1(a)] $A=40.634$ mb and $g_0=0.0106$ produces the putative leading "logarithm-squared-s" term $\sigma_2=68$ mb at the $Sp\bar{p}S$. This is not so far from the correct result of 61.9 mb (Ref. 2). However, σ_2 rises much too fast, being 27 mb at the CERN ISR. In fact, the first nonleading term, $-\sigma_1$, is negative and actually larger than σ_2 at the ISR (-38 mb), while almost canceling it at the $Sp\bar{p}S$ where it is -60 mb. Indeed, $\sigma_{\rm tot}$ can be thought of as due to the second nonleading constant term $\sigma_0=54$ mb with $\sigma_2-\sigma_1$ only a small $\pm 20\%$ perturbation. This is not a scale-free asymptotic description.

Similar comments hold for other asymptotic theories. The critical Reggeon field theory (RFT) predicts the asymptotic form of $\sigma_{\rm tot}$ and $d\sigma_{\rm el}/dt$, with $\sigma_{\rm tot}\sim C(\ln s)^{0.3}$ [Ref. 3(a)]. This is also capable of describing present-energy data with large nonleading terms.[3(b)] Indeed, an asymptotically constant $\sigma_{\rm tot}$ is not ruled out by present data.[1]

The real issue, therefore, seems to us to have more to do with the approach to the asymptotic regime than with the choice of the asymptotic scaling which cannot at present be pinned down with any certainty. Attention should revolve around finite-energy effects, and a description of soft hadron scattering in which scales like s^* arise naturally should be sought. Asymptotic theorems are clearly no help in this matter. Finite-energy models can admit explicit violations of the Froissart bound, which must only be satisfied asymptotically. The fact that Eq. (1) fits the $\sigma_{\rm tot}$ data therefore does not in any sense signify that we are close to a unitarity-saturated asymptotic limit. We are going to present a counterexample which in fact agrees with Eq. (1) in a limited energy region, but deviates from it at other energies.

During approximately the last ten years, following an initial suggestion of Chew and others,[4] we have steadily documented[4–6] a framework which we term the flavored perturbative RFT. It is very important to note that this is not the critical RFT, though it does not preclude the critical RFT from becoming valid at higher energies than the $Sp\bar{p}S$.[3–6] We shall focus on scales like s^* as a central theme. These scales are identified with effective thresholds for appreciable production of pairs of particles with strangeness, baryon number, charm, etc., along with pions. The optical theorem (s-channel unitarity) is employed to make these scales appear in the diffractive amplitude describing elastic scattering. The rise in $\sigma_{\rm tot}$ is then associated with, and strongly constrained by, the inclusive cross sections for the successive emergence of these degrees of freedom. From our point of view, scattering at current energies is far from the asymptotic regime in general, and from black-disk scattering in particular. Hence, there is no reason for absorptive effects to be correlated with and cancel out the flavoring process. Although the details are different, the rise in $\sigma(e^+e^-\rightarrow \text{hadrons})$ and that in $\sigma_{\rm tot}$ for hadron-hadron scattering are ascribed to the common origin of quark-mass effects. The relevant fundamental theory, nonperturbative QCD, cannot yet be employed for calculation of these effects on soft hadron scattering. However, we finesse the difficulty by parametrizing these effects with our data-constrained procedure.

The proper framework for soft hadron scattering here is Regge theory in the presence of soft thresholds. The explicit connection is made through generic strong-coupling cluster multiperipheral-model forms,[4,7] which are known to be the dominant production mechanism for inelastic scattering even at the $Sp\bar{p}S$, where short-range-order correlations in rapidity still dominate.[8] These models can be shown to generate appropriate large values for the scales like s^* [Ref. 5(c)]. The major consequence is a renormalization of the bare Pomeron pole from an "unflavored" $\hat{P}$ with intercept $\hat{\alpha}_0 < 1$ (the leading pole in an auxiliary "unflavored" partial-wave amplitude), to the "flavored" P (the bare Pomeron of the RFT, with intercept $\alpha_0 > 1$). The pole position in a given amplitude is a function of t only—there are no energy-dependent trajectories. The renormalization of α_0 is possible since the bare-Pomeron parameters are nonuniversal in the sense of statistical mechanics,[5(e)] and therefore depend, in principle, on dynamical details like the hadron (or quark) mass and flavor effects. Perturbative corrections to the bare-Pomeron-pole amplitude are provided by j-plane cuts which originate from absorptive corrections to the dominant multiperipheral amplitudes. The largest of these, at present energies, seem to be the absorptive triple-Regge-vertex cut and the (disconnected) second-order eikonal cut.

The general nature of our approach should be emphasized. The perturbative RFT is the appropriate language for any model which begins with a j-plane pole approximation to diffraction and adds perturbative j-plane cuts. Such an approach is called for in the present-energy regime, where short-range-order correlations in rapidity dominate. The flavoring constraints are merely the statement that the correct theory of diffraction must be consistent with unitarity and so must describe the details of inelastic scattering, including the flavor content of the particle production.

The attractiveness of this approach, in our view, is that it provides a framework for a unified description of soft hadron-hadron scattering, both elastic and multiparticle, from the LBL Bevatron to the SPS collider. Among other features, old phase problems with Regge theory at energies below the effective soft flavoring thresholds (below 30 GeV)[9] are avoided naturally[5(a)] by taking $\hat{\alpha}_0 < 1$. Then the renormalized $\alpha_0 > 1$ is calculated such that σ_{tot} rises correctly, consistent with the inclusive cross sections for production of kaon pairs, baryon-antibaryon pairs, charmed-particle pairs, etc., and also including the perturbative absorptive cuts.[5(c),5(d)] Roughly, $\alpha_0 - \hat{\alpha}_0 \approx 0.2$. Recently, a simplified version was proposed[6] in order to extend the model to nonzero (but small) t where no direct constraints exist. This simplified version incorporates Eq. (1) as an approximate description of σ_{tot} from Fermilab to the $Sp\bar{p}S$, though not beyond.

The purpose of this Rapid Communication is to demonstrate for the first time that the details of the shapes of the pp and $p\bar{p}$ $d\sigma_{\text{el}}/dt$ at small $(-t/s)$ can be described in the flavored-perturbative-RFT approach, and closes the last major link in our program. We include a negative-charge-conjugation "odderon"[10] which is not precluded by the RFT. The $p\bar{p}$ data exhibit a distinctly different structure from the dip-bump pattern seen in the pp data. Our model is able to reproduce this behavior from Fermilab to $Sp\bar{p}S$ energies along with σ_{tot} and the forward real to imaginary ratios ρ. Extension to lower-energy two-body data is made with the global fit of Ref. 5(a). To our knowledge, our approach provides the first successful description of all these data.

An important theoretical consequence which emerges from our phenomenology is that an accurate description of diffractive scattering in nonperturbative QCD will have to involve quarks in order to provide the quark-mass-dependent flavoring effects. Therefore, no calculation of the Pomeron involving only glue will be sufficient.[5(f)]

THE SIMPLIFIED FLAVORED-PERTURBATIVE-RFT MODEL

The crossing-even amplitude (we ignore spin) is generally

$$T(s,t) = -\int_{c-i\infty}^{c+i\infty} \frac{dj}{2\pi i} \left(\frac{s}{s_0} e^{-i\pi/2} \right)^j A_j(t) \ , \tag{2}$$

where c is to the right of A_j singularities. The general form for the partial-wave amplitude used in the flavored perturbative RFT for the bare Pomeron is $A_j^{(0)} = N_j/D_j$, where at $t=0$ [Ref. 5 (c)],

$$\begin{aligned} D_j(0) &= j - \hat{\alpha}_0 - \sum_m 2g_m \frac{e^{-b_m(j-\hat{\alpha}_0)}}{(j-j_m)} \ , \\ N_j(0) &= \beta e^{-b_N j}(1+F_{\text{AP}}) \ . \end{aligned} \tag{3}$$

The sum in D_j renormalizes the unflavored intercept $\hat{\alpha}_0$ to α_0 (its leading zero). The couplings g_m produce the pairs ($K\bar{K}$, etc.), which can be seen explicitly by expanding $1/D_j$ in powers of g_m. The exponentials in j generate Θ (Heaviside) functions in $\ln(s)$ when placed in Eq. (2). The parameters j_m occur naturally in strong-coupling cluster multiperipheral models, and phenomenologically ensure that σ_{tot} does not contain any kinks or discontinuities; i.e., the flavoring thresholds are soft. Finally, the N_j function contains terms for associated strangeness and charm production (F_{AP}). To $A_j^{(0)}$ are added the perturbative j-plane cuts. This "unsimplified complete" model does fit σ_{tot} through the $Sp\bar{p}S$ (see Fig. 2 of Ref. 6).

The simplified model of Ref. 6 replaces the sum in D_j by one term, and the parameter j_m is taken as $\hat{\alpha}_0$. The F_{AP} terms in N_j are ignored and $b_N = 0$. No absorptive cuts are included. Then the whole amplitude is continued from $t=0$ to $t<0$ using $\hat{\alpha}(t) = \hat{\alpha}_0 + \hat{\alpha}'t$, the unflavored Pomeron trajectory, and also making g_m and b_m functions of t. Equation (2) can be evaluated by expanding in powers of g_m and using

$$\int_{c-i\infty}^{c+i\infty} \frac{dj}{2\pi i} \frac{e^{jY}}{[j-\hat{\alpha}(t)]^{(n+1)}} = \Theta(Y) \frac{Y^n}{n!} e^{\hat{\alpha}(t) Y} \ , \tag{4}$$

where Y depends on the term evaluated. This model describes the logarithmic $d\sigma_{\text{el}}/dt$ slopes, the ratio of the elastic to total cross section energy dependence, and σ_{tot}. The description of σ_{tot} is immediate, because the simplified model exactly reproduces Eq. (1) in the Fermilab-$Sp\bar{p}S$ region, above s^*, but with $\ln(s/s_0) < 2b_0$ where $b_m(0) = b_0 = \ln(s^*/s_0) = 5.5$. Higher-order terms enter above $2b_0$, but are small for some distance above this value. We interpret the parameter s^* as being between the $K\bar{K}$ and $p\bar{p}$ effective flavoring thresholds, consistent with the relevant data. Then $\hat{\alpha}_0$ must be interpreted, not as the completely unflavored intercept (equal to 0.85 in the P-f-identity model[4,5(a)-5(c)] or 0.91 for the $P+f$ model,[5(d)]) but as renormalized with $K\bar{K}$ flavoring. Detailed phenomenology reveals that with this understanding, $\hat{\alpha}_0 \approx 1$, and the simplified model sets $\hat{\alpha}_0 = 1$.

THE FIT TO THE DATA

The amplitudes for the odderon and an effective absorptive cut are taken to be of the same form as just described for the bare Pomeron. Our odderon also is taken to vanish at $t=0$; it therefore contributes nothing to $\sigma_{\rm tot}$ and does not violate asymptotic theorems, even though these theorems are not of obvious relevance at current energies. The effective cut is supposed to include all perturbative RFT cuts, and is taken for simplicity not to contain any logarithmic terms, either from flavoring or from Regge-cut formalism, which tend in any case to cancel. This could (and should) be refined. The cut contribution turns out small, so our $\sigma_{\rm tot}$ is still accurately described by Eq. (1) and does fit the data. We have also checked that the ρ real-to-imaginary ratios are fit. We write

$$\frac{1}{s}T(s,t)=\sum_{k=P,\ \text{cut, odd}}\left[Ae^{\gamma t}(1+gY^2)\left(\frac{s}{s_0}\right)^{\alpha-1}X(s,t)\right]_k \ . \quad (5)$$

Here,

$$Y=\ln(s/s_0)-b_m,\quad g=g_m/\zeta_m,\quad A\exp(\gamma t)=\beta\zeta_m/s_0\ ,$$

where $\zeta_m=(1-g_m\pi^2/4)$, dropping the k index. We remind the reader that the flavor subscript m has been restricted to one value corresponding to generic flavoring in this simplified model. Also,

$$X(s,t)=(-1+i\eta)\exp(-i\pi\alpha/2)$$

times $(+1,-i)$ for $(+,-)$ signature where

$$\eta=(\pi gY)/(1+gY^2)\ .$$

As in (Ref. 6) we write $g=g_0\exp(g_1t)$ and $b_m(t)=b_0+b't$. The unflavored $\hat{P}$ trajectory

$$\hat{\alpha}(t)=1+\hat{\alpha}'t=1+0.436t$$

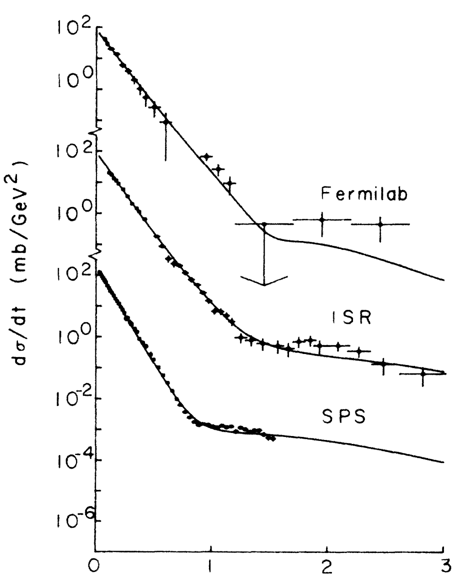

FIG. 1. $d\sigma_{\rm el}/dt$ for $p\bar{p}$ scattering and the fit from the flavored perturbative Reggeon field theory as described in the text. Shown are data at $\sqrt{s}=19.4$ GeV (Fermilab), 52.8 GeV (ISR), and 546 GeV ($Sp\bar{p}S$).

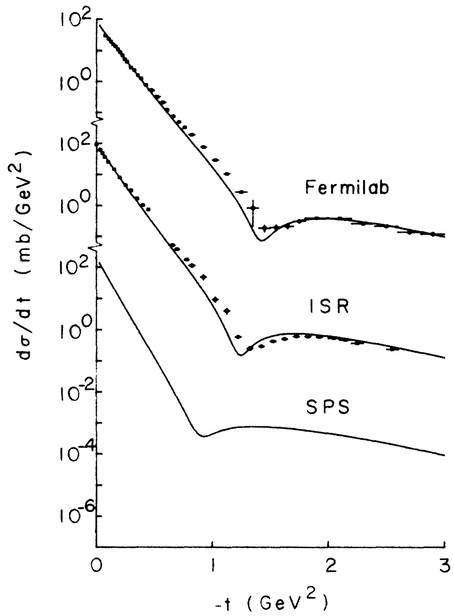

FIG. 2. Same as Fig. 1 for pp scattering with data at $\sqrt{s}=19.4$ and 52.8 GeV.

was fixed,[6] and $A_P, g_{0,P}$ were taken from Eq. (1). The cut trajectory was taken as $1+\hat{\alpha}'t/2$. The odderon $A_{\rm odd}=t^2\tilde{A}_{\rm odd}$ times $(+1,-1)$ for $(pp,p\bar{p})$ scattering and we set $\alpha_{0,\rm odd}=1$, and $b_{0,\rm odd}=b_0$. If $g_k\neq 0$, $0<Y<b_m$ is understood for term k.

The results for the $d\sigma_{\rm el}/dt$ $p\bar{p}$ and pp data[11] from Fermilab to the $Sp\bar{p}S$ are shown in Figs. 1 and 2. The $p\bar{p}$ data are characterized by a rather flat shoulder which rises significantly with energy, and which we fit. The dip-bump structure in pp scattering, with the dip moving inward and the secondary bump moving up with energy, are reproduced reasonably well. The odderon dominates at high s past the dip region, and we therefore stop at $t=-3$ GeV^2. Rather than increase the number of parameters to get a better fit, we felt it preferable to restrict them. Fixing $b'_{\rm odd}$, $g_{1,\rm odd}$, $g_{\rm cut}$, $\gamma_{\rm cut}=0$ and others as noted above, we have eight parameters in the fit: $\gamma_P=3.055$, $g_{1,P}=-1.77$, $b'_P=3.13$, $A_{\rm cut}=-0.325$ mb, $\tilde{A}_{\rm odd}=0.0642$ mb GeV^{-4}, $g_{0,\rm odd}=0.147$, $\gamma_{\rm odd}=1.325$, $\alpha'_{\rm odd}=0.0226$ (with γ, g_1, b', α' in GeV^{-2}).

We repeat that we are using only a simplified version of the flavored perturbative RFT. Furthermore, we have not included the usual secondary Reggeons (ω, . . .) which play some role at Fermilab. Overall, we feel that the agreement we obtain is quite satisfactory.

SUMMARY

In summary, the flavored perturbative Reggeon field theory is capable of describing the shapes of $d\sigma_{\rm el}/dt$ and $\sigma_{\rm tot}$, and a great deal of other soft hadron scattering data through the SPS collider. The simplified version we adopt reproduces the "logarithm-squared-s" $\sigma_{\rm tot}$, including the necessary large scale s^* in the Fermilab-$Sp\bar{p}S$ region; but in our scenario it is clear that this is only a finite-energy and transitory form. Around or perhaps somewhat above the $Sp\bar{p}S$, the flavor-renormalized bare Pomeron s^{α_0-1} takes over until absorptive cuts with increasing relative strength to the bare Pomeron eventually restore the Froissart bound either by saturating it or not saturating it, as is the case with the critical RFT. In any case, we feel that the behavior of diffraction scattering at supercollider energies is by no means a closed subject.

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