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Pomeron intercept and slope: A QCD connection

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The ratio r of intercept to slope of the Pomeron trajectory is derived in a QCD inspired parton model approach to diffraction based on a (re)normalization of the $pp/\bar{p}p$ single-diffractive cross section designed to enforce unitarity constraints by eliminating overlapping rapidity gaps. As the collision energy increases, the renormalized single-diffractive cross section tends to a constant which depends on the ratio r. Identifying the constant as the σ_o of the total cross section, $\sigma = \sigma_o \cdot s^\epsilon$, yields the ratio r in terms of measured parameters that can be phenomenologically expressed in terms of the pion mass and QCD color factors. The result agrees with the measured value of r.

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I. INTRODUCTION

Hadronic diffraction has traditionally been treated in the framework of Regge theory [1–3]. In this approach, diffractive processes at high energies are formally described by the exchange of the *Pomeron trajectory*, presumed to be formed by a *family* of particles carrying the quantum numbers of the vacuum. Although no particles were known to belong to this family, the Pomeron trajectory was introduced in the 1970s to account for the observations that the K^+p cross section was found to be increasing with energy at the Serpukov 70 GeV ($\sqrt{s} = 11.5$ GeV for pp collisions) proton synchrotron, and the elastic and total pp cross sections, which at low energies were falling with increasing energy, started to flatten out and then began to rise as collision energies up to $\sqrt{s} = 60$ GeV became available at the Intersecting Storage Rings at CERN.

In the long history of hadronic diffraction spanning a period of nearly a half century, the intercept $\alpha_{\mathbb{P}}(0) = 1 + \epsilon$ of the Pomeron trajectory $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$, as determined from elastic and total pp and $\bar{p}p$ cross sections, was found to increase with increasing energy from an initial value close to unity to the value of $\alpha_{\mathbb{P}}(0) \approx 1.08$ [4], while the slope parameter $\alpha'_{\mathbb{P}}$ gradually decreased from $\sim 1\ (\mathrm{GeV}/c)^{-2}$ at $\sqrt{s} \sim 5$ GeV (see [5]) to reach a stable value of $\alpha'_{\mathbb{P}} \approx 0.25\ (\mathrm{GeV}/c)^{-2}$ at pp and $\bar{p}p$ collider energies (see [3]). In contrast, the Reggeon trajectories formed by the known mesons and resonances have maintained a constant $\alpha'_R \approx 1\ (\mathrm{GeV}/c)^{-2}$. To date, no particle or resonance that lies on the Pomeron trajectory has yet been positively identified.

The small value of $\alpha'_{\mathbb{P}}$ relative to α'_R remains a theoretical puzzle, whose phenomenological interpretation may provide a clue to understanding the underlying QCD nature of diffraction. In this paper, we present a QCD inspired parton model approach that relates $\alpha'_{\mathbb{P}}$ to ϵ.

In Secs. II, III, IV, V, and VI below, we discuss the Regge approach, the scaling properties and renormalization of diffractive cross sections, the parton model approach, the ratio of α'/ϵ, and conclude with a brief summary.

II. REGGE APPROACH

In Regge theory, high energy hadronic cross sections are dominated by Pomeron exchange. For pp interactions, the Pomeron exchange contribution to the total, elastic, and single diffractive cross sections is given by

$$\sigma^{\mathrm{tot}}(s) = \beta^2(0)\left(\frac{s}{s_\circ}\right)^{\alpha_{\mathbb{P}}(0)-1} \Rightarrow \sigma_\circ\left(\frac{s}{s_\circ}\right)^{\epsilon}, \tag{1}$$

$$\frac{d\sigma^{\mathrm{el}}(s,t)}{dt} = \frac{\beta^4(t)}{16\pi}\left(\frac{s}{s_\circ}\right)^{2[\alpha_{\mathbb{P}}(t)-1]}, \tag{2}$$

$$\frac{d^2\sigma_{\mathrm{sd}}(s,\xi,t)}{d\xi dt} = \underbrace{\frac{\beta^2(t)}{16\pi}\xi^{1-2\alpha_{\mathbb{P}}(t)}}_{f_{\mathbb{P}/p}(\xi,t)}\underbrace{\beta(0)g(t)\left(\frac{s'}{s_\circ}\right)^{\epsilon}}_{\sigma^{\mathbb{P}p}(s',t)}. \tag{3}$$

The differential diffractive cross section, Eq. (3), consists of two terms: the one on the right, $\sigma^{\mathbb{P}p}(s',t)$, which may be viewed as the $\mathbb{P}$-p total cross section, and the term on the left, $f_{\mathbb{P}/p}(\xi,t)$, which is interpreted as the Pomeron flux emitted by the diffractively scattered proton [6]. The parameters in Eq. (3) are defined as follows:

(i) $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} \cdot t = (1+\epsilon) + \alpha'_{\mathbb{P}} \cdot t$ is the Pomeron trajectory;

(ii) $\beta(t) \equiv \beta_{\mathbb{P}pp}(t)$ is the coupling of the Pomeron to the proton usually expressed as $\beta^2(t) = \sigma_\circ \cdot e^{b_\circ t}$, where $\sigma_\circ \equiv \beta^2(0)$ and $e^{b_\circ t}$ is an exponential expression for the form factor of the diffractively escaping proton, $F_p^2(t) = e^{b_\circ \cdot t}$;

(iii) $g(t)$ is the triple Pomeron ($\mathbb{PPP}$) coupling;

(iv) $s' \equiv M^2$ is the $\mathbb{P}$-p center of mass system energy squared, where M is the mass of the diffractively excited proton;

(v) $\xi \approx M^2/s$ is the fraction of the momentum of the incident proton carried by the Pomeron; and

(vi) $s_\circ$ is an energy scale parameter traditionally set to 1 GeV^2.

In analogy with Eq. (1), the $\sigma^{\mathbb{P}p}(s't)$ is written as

$$\sigma^{\mathbb{P}p}(s',t) = \beta_{\mathbb{P}pp}(0)g(t)\left(\frac{s'}{s_\circ}\right)^{\epsilon} = \sigma_\circ^{\mathbb{P}p}(t)\left(\frac{s'}{s_\circ}\right)^{\epsilon},$$
$$\sigma_\circ^{\mathbb{P}p}(t) \Rightarrow \sigma_\circ^{\mathbb{P}p}, \tag{4}$$

where $\sigma_\circ^{\mathbb{P}p}(t)$ is set to a constant, $\sigma_\circ^{\mathbb{P}p}$, as it has been shown to be independent of t [7].

Regge theory was successful in describing elastic, diffractive and total hadronic cross sections at energies up to $\sqrt{s} \sim 60$ GeV, with all processes accommodated in a simple Pomeron pole approach, as summarized in Ref. [5]. Results from an experiment on photon dissociation on hydrogen [8] were also well described by this approach. However, the early success of Regge theory was precarious. The theory was known to asymptotically violate unitarity, as the $\sim s^\epsilon$ power law increase of the total hadron-hadron cross sections would eventually exceed the Froissart bound of $\sigma_T < \frac{\pi}{m_\pi^2} \cdot \ln^2 s$, which is based on analyticity and unitarity.

The confrontation of Regge theory with unitarity came at much lower energies than what would be considered *asymptopia* by Froissart bound considerations. As collision energies climbed upwards in the 1980s to reach $\sqrt{s} = 630$ GeV at the CERN S$\bar{p}p$S collider and $\sqrt{s} = 1800$ GeV at the Fermilab Tevatron $\bar{p}p$ collider, diffraction dissociation could no longer be described by Eq. (3), signaling a breakdown of factorization. The first clear experimental evidence for a breakdown of factorization in Regge theory was reported by the CDF Collaboration in 1994. In a measurement of the single diffractive cross section in $\bar{p}p$ collisions [9], CDF found a suppression factor of ~ 5 (~ 10) at $\sqrt{s} = 546$ GeV (1800 GeV) relative to predictions based on extrapolations from $\sqrt{s} \sim 20$ GeV (see [11–13]).

III. SCALING PROPERTIES AND RENORMALIZATION

The breakdown of factorization in Regge theory was traced back to the energy dependence of the single diffractive cross section, $\sigma_{sd}^{tot}(s) \sim s^{2\epsilon}$, which is faster than that of the total cross section, $\sigma^{tot}(s) \sim s^\epsilon$, so that as s increased unitarity would be violated if factorization held. This can be seen more clearly in the $s^{2\epsilon}$ dependence of $d\sigma_{sd}(M^2, t)/dM^2|_{t=0}$ of the cross section obtained from Eq. (3) by a change of variables from ξ to M^2 using $\xi = M^2/s$:

$$\text{Regge}: d\sigma_{sd}(M^2, t)/dM^2|_{t=0} \sim s^{2\epsilon}/(M^2)^{1+\epsilon}. \quad (5)$$

In 1995 it was shown [10–12] that unitarization could be achieved and the factorization breakdown in single diffraction dissociation fully accounted for by interpreting the Pomeron flux of Eq. (3) as a probability density and *renormalizing* it so that its integral over ξ and t could not exceed unity:

$$f_{\mathbb{P}/p}(\xi, t) \Rightarrow N_s^{-1} \cdot f_{\mathbb{P}/p}(\xi, t) \quad (6)$$

$$N_s \equiv \int_{\xi(\min)}^{\xi(\max)} d\xi \int_{t=0}^{-\infty} dt f_{\mathbb{P}/p}(\xi, t) \sim s^{2\epsilon}/\ln s. \quad (7)$$

Here, $\xi(\min) = M_\circ^2/s$, where $M_\circ^2 = 1.4$ GeV^2 is the effective threshold for diffraction dissociation, and $\xi(\max) = 0.1$ [12]. With a Pomeron flux integral $\sim s^{2\epsilon}/\ln s$, the s dependence introduced through the renormalization factor N_s^{-1} replaces the power law factor $s^{2\epsilon}$ in Eq. (5) by $\ln s$ ensuring unitarization:

$$d\sigma_{sd}(M^2, t)/dM^2|_{t=0} \overset{\text{RENORM}}{\longrightarrow} \sim \ln s/(M^2)^{1+\epsilon}. \quad (8)$$

In the QCD inspired parton model approach presented in Sec. IV, this renormalization procedure eliminates overlapping rapidity gaps caused by multiple Pomeron emissions while preserving the (ξ, t), or (M^2, t), dependence of the differential cross section.

In Fig. 1 (from Ref. [12]), $\sigma_{sd}^{tot}(s)$ is compared with Regge predictions using the standard and renormalized Pomeron flux factors. The renormalized flux prediction is in excellent agreement with the data. An important aspect of renormalization is that it leads to a scaling behavior whereby $d\sigma_{sd}(M^2)/dM^2$ has no power law dependence on s. This "scaling law" holds for the differential soft single diffractive cross section as well, as shown in Fig. 2 (from Ref. [13]).

The elastic and total cross sections are not affected by the renormalization procedure presented here. Unitarization for the elastic and total cross sections may be achieved using an eikonal approach, e.g. as reported in Ref. [14] where excellent agreement is obtained between $p^\pm$, $\pi^\pm$, and $K^\pm$ cross section data and the corresponding predictions based on Regge theory and eikonalization.

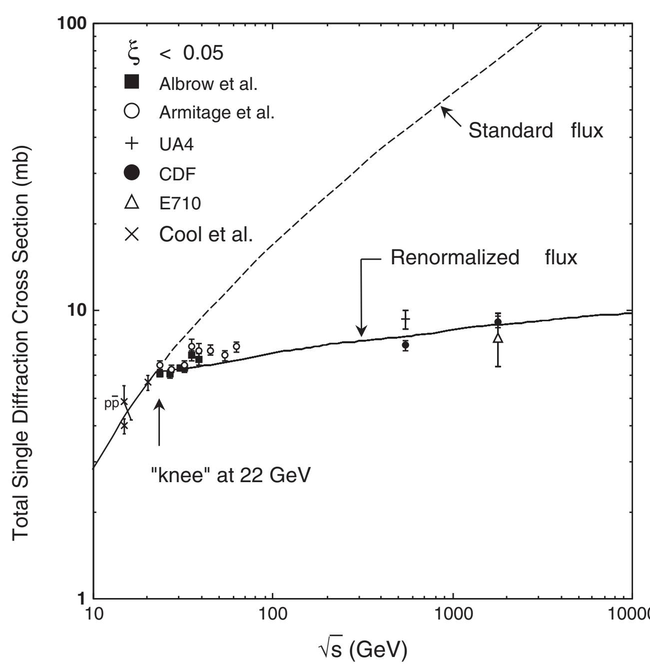

FIG. 1. Total $pp/\bar{p}p$ single diffraction dissociation cross section data (both $\bar{p}$ and p sides) for $\xi < 0.05$ compared with predictions based on the standard and the renormalized Pomeron flux [12].

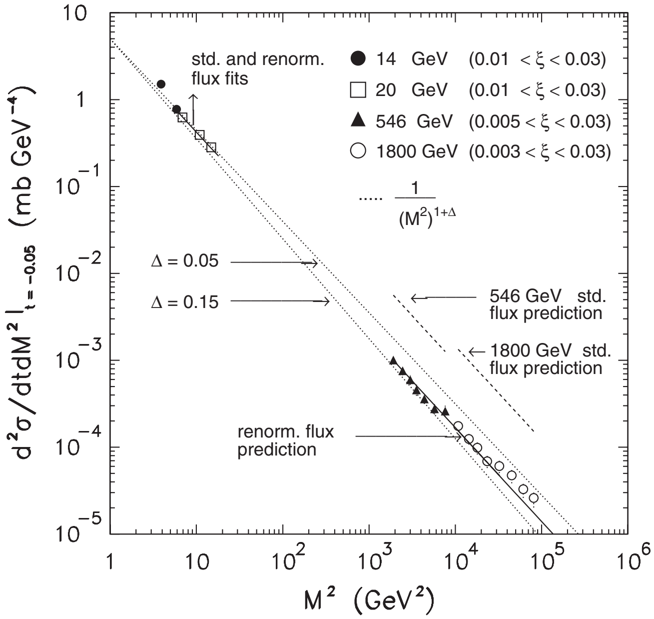

FIG. 2. Cross sections $d^2\sigma_{sd}/dM^2dt$ for $p + p(\bar{p}) \to p(\bar{p}) + X$ at $t = -0.05$ GeV^2 and $\sqrt{s} = 14$, 20, 546, and 1800 GeV. Standard (renormalized) flux predictions are shown as dashed (solid) lines. At $\sqrt{s} = 14$ and 20 GeV, the fits using the standard and the renormalized flux coincide [13].

The features of the data displayed in Figs. 1 and 2 are obtained below in the parton model approach to diffraction. As these features are used to derive the ratio of ϵ to α', they play a crucial role in validating the model.

IV. PARTON MODEL APPROACH

The Regge theory form of the rise of the total $pp/\bar{p}p$ cross sections at high energies, $\sigma^{\rm tot}_{pp/\bar{p}p}(s) = \sigma_\circ \cdot s^\epsilon$, which requires a Pomeron trajectory with intercept $\alpha(0) = 1 + \epsilon$, is precisely the form expected in a parton model approach, where cross sections are proportional to the number of available "wee" (lowest energy) partons. In [15], the parton model cross section is obtained as $\sigma^{\rm tot}_{pp/\bar{p}p} = N \times \sigma_\circ$, where N is the flux of wee partons and $\sigma_\circ$ the cross section of a wee parton interacting with the target proton. The wee partons originate from emissions of single partons cascading down to lower energy partons in treelike chains. The average spacing in (pseudo)rapidity [16] between two successive parton emissions is $\sim 1/\alpha_s$, where α_s is the strong coupling constant. This spacing governs the wee parton density in the η region where particles are produced, defined here as $\Delta\eta'$, which in the case of the total cross section is equal to $\Delta\eta = \ln s$ and leads to a total pp cross section of (see [15]):

$$\sigma^{\rm tot}_{pp/\bar{p}p} = \sigma_\circ \cdot e^{\epsilon \Delta\eta}. \tag{9}$$

This expression is similar to the Regge theory Pomeron contribution to the total cross section. Since from the optical theorem $\sigma^{\rm tot}_{pp/\bar{p}p}$ is proportional to the imaginary part of the forward ($t = 0$) elastic scattering amplitude, the full parton model amplitude may be written as

$$\mathrm{Im}\, f^{\rm el}_{pp/\bar{p}p}(t, \Delta\eta) \sim e^{(\epsilon + \alpha' t)\Delta\eta}, \tag{10}$$

where $\alpha'(t)$ is introduced as a simple linear parametrization of the t dependence. The parameter α' reflects the transverse size of the cluster of wee partons in a chain, which is governed by the $\Delta\eta$ spacing between successive chains and is thereby related to the parameter ϵ.

For the relationship between α' and ϵ we turn to single diffraction dissociation, which through the coherence requirement isolates the cross section from a single wee parton interacting with the proton, since all possible interactions of the remaining wee partons are shielded by the formation of the diffractive rapidity gap. Based on the amplitude of Eq. (10), the single diffractive cross section in the parton model approach takes the form:

$$\frac{d^2\sigma_{\rm sd}(s, \Delta\eta, t)}{dt d\Delta\eta} = \frac{1}{N_{\rm gap}(s)} \times \underbrace{C_{\rm gap} \cdot F_p^2(t)\{e^{(\epsilon+\alpha' t)\Delta\eta}\}^2}_{P_{\rm gap}(\Delta\eta, t)} \cdot \kappa \cdot [\sigma_\circ e^{\epsilon \Delta\eta'}], \tag{11}$$

where:

(i) the factor in square brackets represents the cross section due to the wee partons in the η region of particle production $\Delta\eta'$;

(ii) $\Delta\eta = \ln s$-$\Delta\eta'$ is the rapidity gap;

(iii) κ is a QCD color factor selecting color-singlet gg or $q\bar{q}$ exchanges to form the rapidity gap;

(iv) $P_{\rm gap}(\Delta\eta, t)$ is a gap probability factor representing the elastic scattering between the dissociated proton (cluster of dissociation particles) and the surviving proton;

(v) $N_{\rm gap}(s)$ is the integral of the gap probability distribution over all phase space in t and $\Delta\eta$;

(vi) $F_p^2(t)$ in $P_{\rm gap}(\Delta\eta, t)$ is the proton form factor defined in the discussion of the parameters that appear in the Pomeron flux in Eq. (3); and

(vii) $C_{\rm gap}$ is a normalization constant, whose value is rendered irrelevant by the renormalization division by $N_{\rm gap}(s)$.

Since $\Delta\eta = -\ln\xi$, the form of Eq. (11) is identical to the Regge form of Eq. (3). This identifies $C_{\rm gap}$ and $\kappa\sigma_\circ$ as $\sigma_\circ/16\pi$ and $\sigma_\circ^{\mathbb{P}p}$, respectively. However, there is an important difference from the Regge expression, namely, the renormalization factor introduced in Sec. III.

The traditional way to proceed would have been to consider single diffraction as the elastic scattering between the dissociated and escaping protons and use the eikonal procedure to achieve unitarity. The first attempt to apply such a unitarization scheme [17] failed to describe the energy dependence of $\sigma_{\rm sd}$ (see [13]). Subsequently, several different eikonal models were introduced to incorporate diffraction dissociation, but to date no complete agreement has been reached among the proponents of such models [18]. Interpreting $P_{\rm gap}(\Delta\eta, t)$ in Eq. (11) as a gap formation probability whose integral over all phase space saturates at unity offers a transparent and effective way of unitarizing diffraction. Moreover, this formulation of the parton model approach to diffraction is directly applicable to central and multigap diffractive processes, as shown in the review of Ref. [19]. The predictions of the model extend to pseudorapidity, multiplicity, and E_T distributions of single and double gap soft diffraction processes [19]. For these reasons, we adopt the renormalization procedure as an axiom whose predictions the more rigorous theoretical approaches to diffraction will have to reproduce if they are to agree with the available experimental data.

It should be emphasized that our approach is a simple phenomenological interpretation of the parton model as it applies to diffraction. Renormalization ensures that once a gap is formed by a color-singlet exchange, another such exchange that could have formed a gap in the same event cannot contribute to the cross section. Theoretically, this represents a saturation effect, which is accounted for by the removal of overlapping rapidity gaps. While this concept cannot readily be represented by simple Feynman diagrams, it can nevertheless provide useful constraints to traditional parton model QCD approaches. Guided by the experimental results [19], we assume that the probability of having multiplicity fluctuations in parton cascades to much larger than the average multiplicity that would spoil this picture is suppressed.

Below, in Sec. V, the factor κ of Eq. (11) is expressed in Eq. (16) in terms of the (soft scale) gluon and quark fractions of the proton weighted by the corresponding QCD color factors, ensuring a fully QCD based phenomenological description of the differential single diffraction dissociation cross section on which the derivation of the ratio of slope to intercept rests.

V. THE RATIO OF α'/ϵ

By a change of variables from $\Delta\eta$ to M^2 using $\Delta\eta' = \ln M^2$ and $\Delta\eta = \ln s - \ln M^2$, Eq. (11) takes the form

$$\frac{d^2\sigma_{\rm sd}(s, M^2, t)}{dM^2 dt} = \left[\frac{\sigma_\circ}{16\pi}\sigma_\circ^{\mathbb{P}p}\right]\frac{s^{2\epsilon}}{N(s)}\frac{1}{(M^2)^{1+\epsilon}}e^{bt}$$
$$\stackrel{s\to\infty}{\Rightarrow}\left[2\alpha' e^{(\epsilon b_0)/\alpha'}\sigma_\circ^{\mathbb{P}p}\right]\frac{\ln s^{2\epsilon}}{(M^2)^{1+\epsilon}}e^{bt}, \tag{12}$$

where $b = b_\circ + 2\alpha' \ln\frac{s}{M^2}$. Integrating this expression over M^2 and t yields the total single diffractive cross section,

$$\sigma_{\rm sd} \stackrel{s\to\infty}{\to} 2\sigma_\circ^{\mathbb{P}p}\exp\left[\frac{\epsilon b_\circ}{2\alpha'}\right] = {\rm const} \equiv \sigma_{\rm sd}^\infty. \tag{13}$$

The remarkable property that the total single diffractive cross section becomes constant as $s\to\infty$ is a direct consequence of the coherence condition required for the recoil proton to escape the interaction intact. This condition selects one out of several available wee partons to provide a color shield to the exchange and enable the formation of a diffractive rapidity gap. The selection of one of the partons of the outgoing proton identifies the constant $\sigma_{\rm sd}^\infty$ as the $\sigma_\circ$ of Eq. (9), since this is the part of the total cross section that does not contain any wee parton contributions. The parameter $\sigma_\circ$ is specific to the dissociating particle, which in this case is the proton and therefore equals $\sigma_\circ^{pp}$. We thus have

$$\sigma_{\rm sd}^\infty = 2\sigma_\circ^{\mathbb{P}p}\exp\left[\frac{\epsilon b_\circ}{2\alpha'}\right] = \sigma_\circ^{pp}, \tag{14}$$

which is the sought after relationship between ϵ and α' in terms of constants which can be deduced from QCD parameters through the relationships

$$\sigma_\circ^{\mathbb{P}p} = \beta_{\mathbb{P}pp}(0)\cdot g(t) = \kappa\sigma_\circ^{pp} \tag{15}$$

$$\kappa = \frac{f_g^\infty}{N_c^2 - 1} + \frac{f_q^\infty}{N_c} \tag{16}$$

$$b_\circ = R_p^2/2 = 1/(2m_\pi^2). \tag{17}$$

Here, the color factor κ is expressed in terms of the gg and $q\bar{q}$ color factors weighted by the corresponding gluon and sea-quark fractions, and R_p is the radius of the proton expressed in terms of the pion mass m_π. The fractions f_g^∞ and f_q^∞, where the superscript indicates the limit $s\to\infty$, as in Eq. (13), are extracted from the CTEQ5L [20] parametrizations of the corresponding nucleon parton distribution functions $x\cdot f(s)$ at a scale of $Q^2\sim 1$ GeV^2, considered the appropriate scale for the soft pp and $\bar{p}p$ scattering that is being discussed (see [19], Sec. 5.1). Inserting these parameters in Eq. (13) yields

$$r = \frac{\alpha'}{\epsilon} = -[16m_\pi^2\ln(2\kappa)]^{-1}. \tag{18}$$

The above equation, in which r is expressed in terms of the mass of the pion and the parameter κ which depends on QCD color factors and the gluon and sea-quark fractions of the underlying parton distribution function of the nucleon, represents the sought after "QCD connection" between the Pomeron intercept and its slope. For a numerical estimate of r, we use $m_\pi = 0.14$ GeV$/c^2$ and $\kappa = 0.18\pm 0.02$, as obtained for gluon and quark fractions of $f_g^\infty = 0.75$ and $f_q^\infty = 0.25$ evaluated from the CTEQ5L nucleon parton distribution function (see [19] Sec. 5.1). The uncertainty in κ is due to an estimated uncertainty of 10% in the gluon fraction and a corresponding uncertainty in the quark fraction as constrained by $f_g^\infty + f_q^\infty = 1$. Using these values yields $r_{\rm pheno} = 3.2\pm 0.4$ (GeV$/c)^{-2}$.

This result is in excellent agreement with the ratio calculated from the values of $\epsilon = 0.08$ and $\alpha'_{\mathbb{P}} = 0.25\ (\mathrm{GeV}/c)^{-2}$ for the soft Pomeron trajectory obtained from fits to experimental data of total and elastic pp and $\bar{p}p$ cross sections for collision energies up to $\sqrt{s} = 540$ GeV, $r_{\mathrm{exp}} = 0.25\ (\mathrm{GeV}/c)^{-2}/0.08 = 3.13\ (\mathrm{GeV}/c)^{-2}$ [4]. The smaller value for r_{exp} obtained from a global fit to $p^{\pm}p$, $\pi^{\pm}p$, and $K^{\pm}p$ cross sections, $r_{\mathrm{exp}}(\text{global fit}) = 0.26\ (\mathrm{GeV}/c)^{-2}/0.104 =$
$2.5\ (\mathrm{GeV}/c)^{-2}$ [14], is presumed to be due to the increase of the intercept from the additional radiation from hard (high Q^2) partonic exchanges at higher energies, as, for example, manifested in the two-Pomeron model of Ref. [21].

VI. SUMMARY

In a QCD based parton model approach to elastic, diffractive, and total cross sections, interactions occur through the emission of partons, which cascade down to wee partons in chains of treelike configurations. As the spacing between successive emissions is controlled by the strong coupling constant, the total cross section, which is proportional to the number of wee partons produced, assumes a power law behavior similar to that of Regge theory. This partonic description is used in this paper to relate the Pomeron intercept of Regge theory to the underlying parton distribution function. The transverse size of the cluster of wee partons in a chain originating from one such emission, which is the source of the slope parameter α' of the Pomeron trajectory, depends on the distance in (pseudo)rapidity space between successive emissions and thereby on the parameter ϵ. Exploiting single diffraction, which through the coherence requirement isolates a partonic chain due to a single parton emission, the ratio of α' to ϵ is derived in terms of the pion mass m_{π} and a QCD color factor κ appropriately weighted by the gluon and quark fractions of the proton at the soft scale of $Q^2 \sim 1\ \mathrm{GeV}^2$, as obtained from the CTEQ5L parametrization of the nucleon parton distribution function. The derived value of the ratio of α'/ϵ, $r_{\mathrm{pheno}} = 3.12 \pm 0.4\ (\mathrm{GeV}/c)^{-2}$, is in excellent agreement with the experimental value of $r_{\mathrm{exp}} = 3.13\ (\mathrm{GeV}/c)^{-2}$.

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