

# Hard Pomeron impact on the high-energy elastic scattering of nucleons

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The role of the hard Pomeron (HP) exchanges in the high-energy diffractive interaction of nucleons is explored. It is demonstrated that the HP subdominance at available energies and low transferred momenta are due to the extremely low slope of its Regge trajectory.

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## I. INTRODUCTION

In the framework of Regge phenomenology [1], the observed growth of the  $pp$  total and elastic cross sections at collision energies higher than 20 GeV [2] is explained in terms of the soft Pomeron exchanges [3,4], where the soft Pomeron (SP) is a supercritical Reggeon with the intercept of its Regge trajectory  $\alpha_{\text{SP}}(0) \approx 1.1$ . By full analogy, the available data on the proton unpolarized structure function  $F_2^p(x, Q^2)$  [5] at high values of the incoming photon virtuality  $Q^2$  and low values of the Bjorken scaling variable  $x$  can be described in terms of another Pomeron (called “hard”) with the intercept  $\alpha_{\text{HP}}(0) = 1.32 \pm 0.03$  [6] or even higher (see, for instance, [7,8], or [9]). In spite of the fact that  $\alpha_{\text{HP}}(0) > \alpha_{\text{SP}}(0)$ , the hard Pomeron (HP) impact on the nucleon-nucleon diffractive scattering seems to be insignificant [4].

An easy way to explain this elusiveness of the HP in high-energy soft interactions is just to presume the suppression of its coupling to hadrons in the nonperturbative regime, which automatically leads to the SP dominance in the diffractive interaction in the absence of a hard scale. However, such a physical pattern seems somewhat exotic since both the Pomerons are apparently composed of gluon matter.<sup>1</sup> Hence, no evident argument exists why their couplings to protons at low transferred momenta should differ greatly by order of magnitude, while the difference between their intercepts is large enough to expect the HP dominance or, at least, significance at the LHC energies.

Below we address the problem of the HP contribution into the  $pp$  high-energy elastic scattering to provide a more natural interpretation of the HP “invisibility” in the soft interaction of hadrons than the above-mentioned presumption about the coupling suppression.

## II. THE HP REGGE TRAJECTORY

First of all, let us pay attention to the behavior of the HP Regge trajectory in the asymptotic region  $t \rightarrow -\infty$ .

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<sup>1</sup>The leading meson Regge trajectories of the quark model have intercepts considerably below the unity. A detailed discussion of the gluon nature of supercritical Reggeons can be found in classic papers [10,11].

Presumably, the HP is the leading Reggeon of the Balitzki-Fadin-Kuraev-Lipatov (BFKL) series [12]:

$$\alpha_{\text{BFKL}}^{(n_r)}(t) = 1 + \frac{12 \ln 2}{\pi} \alpha_s(\sqrt{-t}) \left[ 1 - \alpha_s^{2/3}(\sqrt{-t}) \left( \frac{7\zeta(3)}{2 \ln 2} \right)^{1/3} \times \left( \frac{3/4 + n_r}{11 - 2/3N_f} \right)^{2/3} + \dots \right], \quad (1)$$

where  $\alpha_s(\mu)$  is the QCD running coupling,  $N_f$  is the number of quark flavors, and  $n_r$  is the radial quantum number. If  $t = -M_Z^2 = -(91.2 \text{ GeV})^2$ ,  $\alpha_s(M_Z) = 0.118$ ,  $n_r = 0$ , and  $N_f = 5$  or 6, then we obtain

$$\alpha_{\text{HP}}(-M_Z^2) = \alpha_{\text{BFKL}}^{(0)}(-M_Z^2) \approx 1.28. \quad (2)$$

Note that the second term in the brackets on the right-hand side of (1) is  $\sim 0.1$  under the chosen values of the parameters. Thus, the estimation (2) is quite justified.

Comparing the values of  $\alpha_{\text{HP}}(t)$  at  $t = 0$  and  $t = -M_Z^2$ , as well as the quantities  $\alpha'_{\text{HP}}(-M_Z^2) \approx 2 \times 10^{-6} \text{ GeV}^{-2}$  and  $\frac{\alpha_{\text{HP}}(0) - \alpha_{\text{HP}}(-M_Z^2)}{M_Z^2} \approx 5 \times 10^{-6} \text{ GeV}^{-2}$ , one might come to a conclusion that both the functions  $\alpha_{\text{HP}}(t)$  and  $\alpha'_{\text{HP}}(t)$  evolve very slowly in the interval  $-M_Z^2 < t < 0$ . Moreover, even if  $\alpha'_{\text{HP}}(t)$  is essentially nonlinear in the considered range and  $\alpha'_{\text{HP}}(0)$  is, say, 100 times higher than  $\alpha'_{\text{HP}}(-M_Z^2)$ , it is quite reasonable to consider  $\alpha_{\text{HP}}(t) \approx \alpha_{\text{HP}}(0)$  at  $-3 \text{ GeV}^2 < t < 0$ .

Such a weak  $t$  dependence is a very important feature of the HP Regge trajectory, which allows one to make unambiguous conclusions on the basis of further analysis. Also, such a high value of  $\alpha_{\text{HP}}(-M_Z^2)$  points to the fact

TABLE I. The parameter values for (4) obtained via fitting [14] to the high-energy elastic scattering data.

Parameter	Value
$\alpha_{\text{SP}}(0) - 1$	0.109
$\tau_a$	0.535 GeV <sup>2</sup>
$g_{\text{SP}}(0)$	13.8 GeV
$a_g$	0.23 GeV <sup>-2</sup>

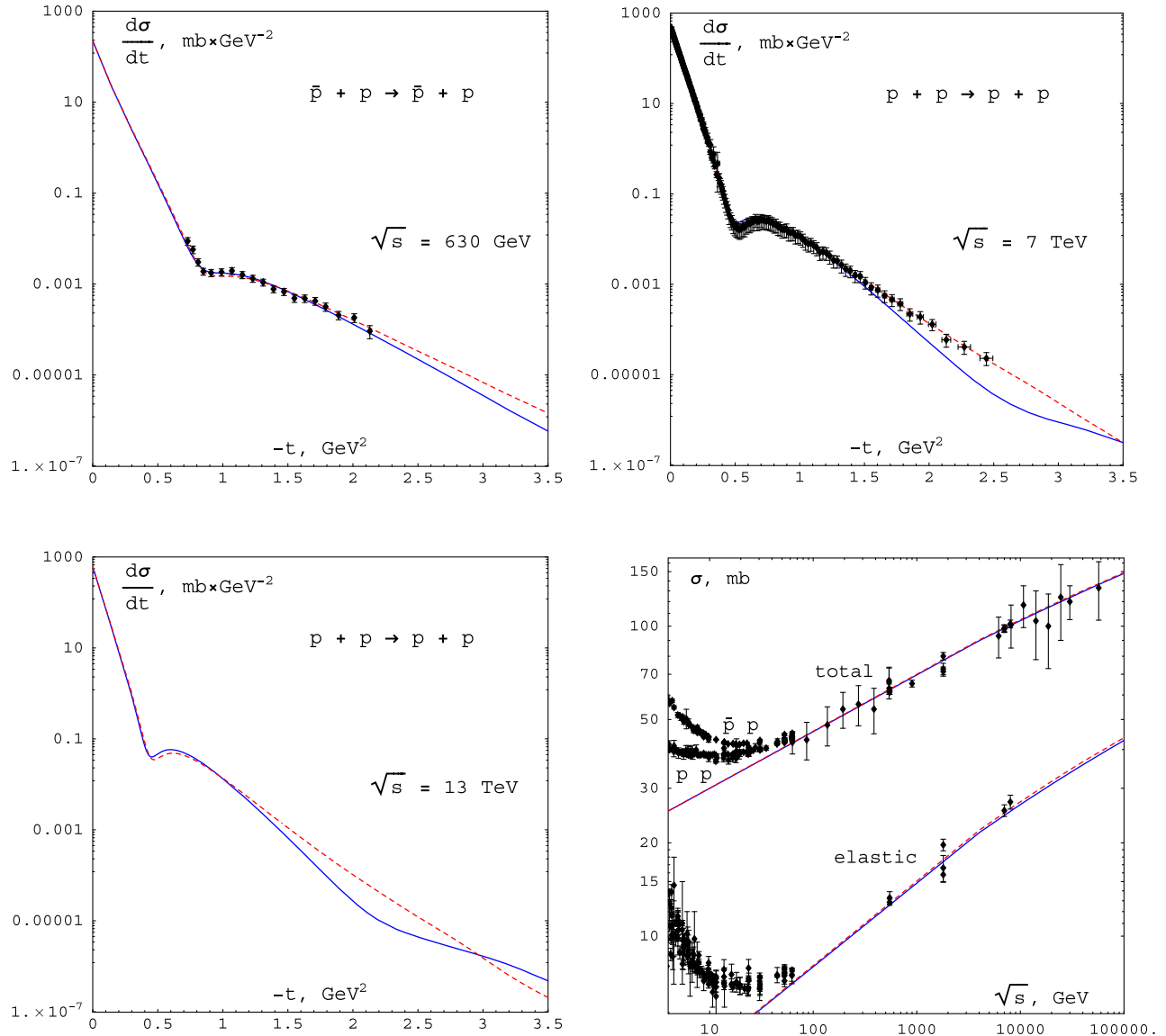


FIG. 1. The HP impact on the observables of nucleon-nucleon scattering [2,15,16]. The used HP parameters are  $\alpha_{\text{HP}}(0) = 1.32$ ,  $\beta_{\text{HP}}(0) = 0.08$ ,  $b = 1.5 \text{ GeV}^{-2}$ . The solid (dashed) lines correspond to the model ignoring (taking account of) the HP exchanges.

that the gluon field self-action must not be ignored even at such high momentum transfers. Otherwise, the HP exchange could be reduced to exchange by two gluons, and the corresponding Born amplitudes would behave as  $\sim s^1$  (for details, see [13]).

### III. THE HP EXCHANGE CONTRIBUTION INTO THE EIKONAL

The soft-Pomeron-exchange eikonal approximation has the following structure [14]:

$$\begin{aligned}
 \frac{d\sigma}{dt} &= \frac{|T(s, t)|^2}{16\pi s^2}, \\
 T(s, t) &= 4\pi s \int_0^\infty db^2 J_0(b\sqrt{-t}) \frac{e^{2i\delta(s, b)} - 1}{2i}, \\
 \delta(s, b) &= \frac{1}{16\pi s} \int_0^\infty d(-t) J_0(b\sqrt{-t}) \delta_{\text{SP}}(s, t) \\
 &= \frac{1}{16\pi s} \int_0^\infty d(-t) J_0(b\sqrt{-t}) g_{\text{SP}}^2(t) \left( i + \tan \frac{\pi(\alpha_{\text{SP}}(t) - 1)}{2} \right) \pi \alpha'_{\text{SP}}(t) \left( \frac{s}{2s_0} \right)^{\alpha_{\text{SP}}(t)}, \tag{3}
 \end{aligned}$$

where  $s$  and  $t$  are the Mandelstam variables,  $b$  is the impact parameter,  $s_0 = 1 \text{ GeV}^2$ ,  $J_0(x)$  is the Bessel function,  $\alpha_{\text{SP}}(t)$  is the Regge trajectory of the soft Pomeron, and  $g_{\text{SP}}(t)$  is the SP coupling to proton. At  $t < 0$ ,  $\alpha_{\text{SP}}(t)$  and  $g_{\text{SP}}(t)$  can be approximated by simple test functions

$$\alpha_{\text{SP}}(t) = 1 + \frac{\alpha_{\text{SP}}(0) - 1}{1 - \frac{t}{\tau_a}}, \quad g_{\text{SP}}(t) = \frac{g_{\text{SP}}(0)}{(1 - a_g t)^2}, \quad (4)$$

where the free parameters take on the values presented in Table I.

Inclusion of the HP exchanges into consideration requires a replacement  $\delta_{\text{SP}}(s, t) \rightarrow \delta_{\text{SP}}(s, t) + \delta_{\text{HP}}(s, t)$ , where

$$\delta_{\text{HP}}(s, t) = \left( i + \tan \frac{\pi(\alpha_{\text{HP}}(0) - 1)}{2} \right) \beta_{\text{HP}}(t) \left( \frac{s}{2s_0} \right)^{\alpha_{\text{HP}}(0)}. \quad (5)$$

Choosing  $\alpha_{\text{HP}}(0) = 1.32$  and  $\beta_{\text{HP}}(t) = \beta_{\text{HP}}(0)e^{bt}$ , where  $\beta_{\text{HP}}(0) = 0.08$  and  $b = 1.5 \text{ GeV}^{-2}$ , we come to the pattern presented in Fig. 1. The description quality is satisfactory: for example,  $\Delta\chi^2 \approx 12$  over 19 points of the data set [15] and  $\Delta\chi^2 \approx 215$  over 205 points of the data set [16]. The description of other data considered in [14] remains satisfactory as well.

As we see, the account of the HP exchanges improves the description of  $d\sigma/dt$  at  $\sqrt{s} = 7 \text{ TeV}$  without any refitting of the SP parameters. Regarding available data at the lower energies, the HP impact can be ignored though.

#### IV. DISCUSSION AND CONCLUSIONS

The HP subdominance at accessible energies is, certainly, determined by the smallness of its Regge residue:

$$\beta_{\text{HP}}(t) = g_{\text{HP}}^2(t) \pi \alpha'_{\text{HP}}(t). \quad (6)$$

Assuming that  $4 < \alpha'_{\text{HP}}(0)/\alpha'_{\text{HP}}(-M_Z^2) < 100$ , we obtain  $g_{\text{HP}}(0) \sim g_{\text{SP}}(0)$ , which is quite natural in view of the presumed glueball nature of both the Pomerons. The smallness of  $\beta_{\text{HP}}(t)$  at low negative  $t$  is, thus, related to the extremely weak  $t$  behavior of  $\alpha_{\text{HP}}(t)$ .

The low  $t$  slope of  $\alpha_{\text{HP}}(t)$  may take place in the region  $t > 0$  as well. It would imply the existence of some series of ultraheavy resonances lying on the HP Regge trajectory. Due to their spin properties, such an ultraheaviness (tens or hundreds of GeV) accomplished by strong enough coupling to light hadrons inevitably results in the ultrashort life of the HP resonance states. The conception of heavy Pomeron is, certainly, not new. It was proposed by Gribov more than 40 years ago [17]. The only difference between Gribov's heavy Pomeron and the BFKL HP is in their intercept values.

Above, we neglected the impact of the subleading (daughter) Pomerons corresponding to nonzero values of  $n_r$  in series (1). The reason is that the leading Pomeron intercept is separated from the subleading ones by a significant gap [18]. A similar pattern takes place for other known series of Reggeons in asymptotically free field theories [19,20]. Moreover, as the Regge trajectories are expected to be Herglotz functions [1], so the contributions of the subleading BFKL Pomerons at nonzero  $n_r$  and low negative  $t$  are suppressed in the factors  $\alpha_{\text{BFKL}}^{(n_r)'}(t)$  [as compared to  $\alpha_{\text{BFKL}}^{(0)'}(t)$ ] in addition to the suppression in the values of  $\alpha_{\text{BFKL}}^{(n_r)}(t)$ . The much higher slope of  $\alpha_{\text{SP}}(t)$  points to the fact that the soft Pomeron is not a Reggeon from the BFKL series.

In view of the aforesaid, we come to the main conclusion. The conception of the hard Pomeron as the leading Reggeon of the BFKL series is quite consistent with the available data on the high-energy  $pp$  elastic scattering. Its ‘‘invisibility’’ at the collision energies lower than 2 TeV is related not to the smallness of its coupling to protons (which is of the same order as the soft Pomeron's one) but to its extremely weak  $t$  evolution in the scattering region. In its turn, such a weak  $t$  behavior seems to be related to a possible ultraheaviness of the resonances corresponding to this Reggeon. Hence, the characteristics ‘‘light’’ and ‘‘heavy,’’ regarding these two Pomerons, seem to be more natural than ‘‘soft’’ and ‘‘hard’’ (though, it is just a matter of conventions in terminology).

Concerning the exploited model range of applicability, it should be mentioned that the used simple parametrizations for  $\alpha_{\text{SP}}(t)$ ,  $g_{\text{SP}}(t)$ , and  $\beta_{\text{HP}}(t)$  are no more than test functions, which are not expected to be valid at high values of  $-t$ . Namely, they are just quantitative nonanalytic approximations to the true functions in the nonperturbative region only. One should keep in mind that the true analytic behavior of  $\alpha_{\text{SP}}(t)$ ,  $g_{\text{SP}}(t)$ , and  $\beta_{\text{HP}}(t)$  is still unknown. As a consequence, the validity of the considered approximations can be determined only via fitting to experimental data.

In the very end, it should be pointed out that the TOTEM data at  $\sqrt{s} = 7 \text{ TeV}$  only do not allow one to confirm or discriminate the used phenomenological estimation of the HP intercept. The problem of absorption was swept under the carpet in [6], though the relative contribution of the absorptive corrections may be nonvanishing in the kinematic range considered in [6]. Therefore, the true value of  $\alpha_{\text{HP}}(0)$  may be a bit higher and, so, the estimation  $\alpha_{\text{HP}}(0) = 1.32 \pm 0.03$  should be treated just as the lower bound for this quantity. For example, the variants  $\alpha_{\text{HP}}(0) = 1.44$  [7] and  $\beta_{\text{HP}}(t) = \beta_{\text{HP}}(0)e^{bt}$ , where  $\beta_{\text{HP}}(0) = 0.01$  and  $b = 1.5 \text{ GeV}^{-2}$ , also yield a satisfactory description of the TOTEM data (see Fig. 2). The data at  $\sqrt{s} = 13 \text{ TeV}$  are needed for a more or less reliable determination of  $\alpha_{\text{HP}}(0)$ . Of course, if more precise data on the proton unpolarized structure function  $F_2(x, Q^2)$  at higher  $Q^2$  and lower  $x$  were

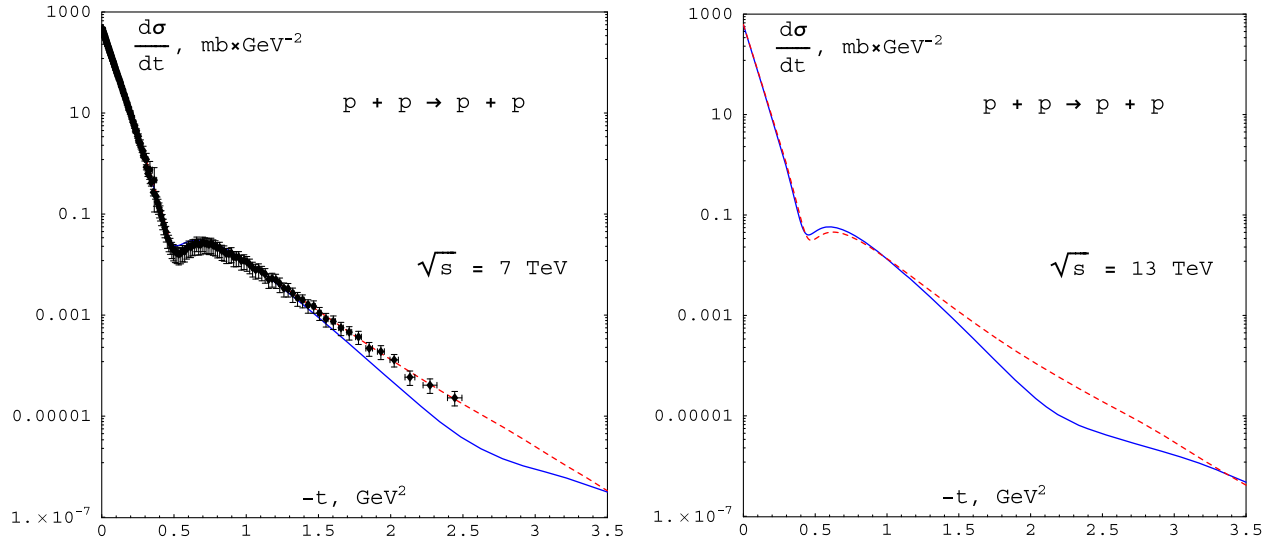


FIG. 2. The HP impact on the differential cross section of  $pp$  elastic scattering at the LHC energies. The used HP parameters are  $\alpha_{\text{HP}}(0) = 1.44$ ,  $\beta_{\text{HP}}(0) = 0.01$ ,  $b = 1.5 \text{ GeV}^{-2}$ . The solid (dashed) lines correspond to the model ignoring (taking account of) the HP exchanges.

available (say, from hypothetical and feasible LHeC Runs), then a more accurate and reliable determination of  $\alpha_{\text{HP}}(0)$  and, consequently, of  $\beta_{\text{HP}}(t)$  would be possible.

In any case, the account of the HP exchanges extends the applicability range of the Regge-eikonal approximation (3), (4) for the elastic scattering of nucleons at ultrahigh energies. The satisfactory reproduction of available data by the updated model demonstrates the incorrectness of the

claim [21] that absorptive models do not provide a good description of the LHC data in the deep-elastic scattering region.

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