A review of the hard pomeron in soft diffraction

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We review the evidence for the presence of a hard singularity in soft forward amplitudes, and give an estimate of its trajectory and couplings.

In 1998, Donnachie and Landshoff showed that DIS data at small x can be described by the superposition of two Regge exchanges : the soft and the hard pomeron, and that both are well approximated by simple poles [1]. Their fit to HERA data then leads to the conclusion that the soft pomeron is a higher-twist contribution. It was further suggested [2] that the DGLAP evolution has to be performed in a non-trivial manner : as it is of perturbative origin, the singularity that it introduces at $J = 1$ should be considered only if one is far away from it, as otherwise perturbation theory breaks down. Applying this philosophy to the evolution leads to a prediction of the Q^2 dependence of the hard pomeron from DGLAP evolution, and to a successful description of F_2 and F_L [3,4], provided that the gluon distribution is associated with the hard pomeron contribution. The obtained fit can then be extended to higher x [3]. This leads to the conclusion that the data at large Q^2 and $t = 0$ contain a sizable contribution from a hard pomeron with intercept

$$\alpha_h(t = 0) \approx 1.4.$$

Furthermore, the same idea can be used to describe F_2^c [5] as well as vector-meson photoproduction [6]. In this case, the main characteristic of the data is a modification of the energy dependence of the cross section as the vector-meson mass increases, and a flattening of the t dependence at high t. Both effects can be interpreted as a signature of the contribution of a hard pomeron, provided it has a rather flat trajectory:

$$\alpha_h(t) \approx 1.4 + 0.1t.$$

The question remained however to understand why such a hard pomeron had not been seen before, and what happened to it at $t = Q^2 = 0$. The first remark is that it is possible to have singularities that manifest themselves only in photon scattering (e.g. that associated with the box diagram in $\gamma\gamma$ scattering). Hence the first place to look is presumably the photon total cross section. Unfortunately, the data from LEP suffer from large theoretical uncertainties linked with the Monte-Carlo simulations used to unfold the data. A fit to the $\gamma\gamma$ data only indicates that the hard pomeron *may* be present, but with a rather small coupling, about 10% that of the soft pomeron [1]. However, it seems rather strange that a hadronic object like a hard pomeron should decouple fully from total hadronic cross sections. One might argue that this has something to do with the point structure of the photon coupling, but nevertheless it would be reassuring to find such a contribution in purely hadronic cross sections.

Bounds on the hard pomeron have been known for a long time: the ratio of its coupling to that of pp and $\bar{p}p$ was estimated to be less than 2×10^{-6} [7]. Furthermore, recent studies [8] of hadronic amplitudes down to $\sqrt{s} = 5$ GeV dismiss models based on a simple-pole pomeron, mainly because they cannot describe the real part of the amplitude well, or equivalently because the fit to ρ, the ratio of the real part to the imaginary part of the elastic hadronic amplitude, has an unacceptably high χ^2.

We revisited this problem [9] first by improving the treatment of the real part of the amplitude:

• We included and fitted the subtraction constant present in the real part of the amplitude because of rising $C = +1$ contributions.

• We used integral dispersion relations down to the correct threshold and, at low energies (for which the analytic asymptotic model is not correct), we used (a smooth fit to) the data for σ_{tot} to perform the dispersion integral.

• We used the exact form of the flux factor $\mathcal{F} = 2m_p p_{lab}$ and Regge variables $\tilde{s} \equiv \frac{s-u}{2}$ proportional to $\cos(\theta_t)$ instead of their dominant terms at large-s[1].

Following [8], we fit total cross sections and ρ for pp, $\bar{p}p$, $\pi^{\pm}p$ and $K^{\pm}p$, and total cross sections for γp and $\gamma\gamma$ in the region $\sqrt{s} \geq 5$ GeV. Furthermore, as we are using simple poles, we use Gribov-Pomeranchuk factorisation of the residues at each simple pole to predict the $\gamma\gamma$ amplitude from the pp and γp data [10].

If we define the hadronic ab amplitude as $\mathcal{A}_{ab} = \Re_{ab} + i\Im_{ab}$, we obtain the total cross section as $\sigma_{tot}^{ab} \equiv \Im^{ab}/(2m_b p_{lab})$, with p_{lab} the momentum of particle b in the a rest frame, and the models that we consider are defined by the following equation:

$$\Im_{ab} \equiv s_1 \left[\Im_{ab}^{R+}\left(\frac{\tilde{s}}{s_1}\right) + \Im_{ab}^{S}\left(\frac{\tilde{s}}{s_1}\right) \mp \Im_{ab}^{-}\left(\frac{\tilde{s}}{s_1}\right) \right], \quad (1)$$

with $s_1 = 1$ GeV^2, and the $-$ sign in the last term for particles. For the two reggeon contributions $\Im^{R+}$ and $\Im_{ab}^{-}$, we use (non-degenerate) simple-pole expressions. For the pomeron contribution $\Im_{ab}^{S}$, we allow two simple poles to contribute:

$$\Im_{pb}^{S} = S_b \left(\frac{\tilde{s}}{s_1}\right)^{\alpha_o} + H_b \left(\frac{\tilde{s}}{s_1}\right)^{\alpha_h} \quad (2)$$

For comparison, we also consider expressions corresponding to a dipole $\Im_{pb}^{S} = (\tilde{s}/s_1) D_b \log(\tilde{s}/s_d)$ or a tripole $\Im_{pb}^{S} = (\tilde{s}/s_1) T_b \left[\log^2(\tilde{s}/s_t) + t_b'\right]$.

[1]In the $\gamma\gamma$ case, we use $\mathcal{F} = s$

The improved treatment of ρ leads to a better fit in all cases (a dipole pomeron reaches a χ^2/dof of 0.94 and a tripole pomeron one of 0.93, whereas they were both 0.98 in the standard analysis [8]). However, if we use only one simple pole for the pomeron (*i.e.* if we set $H_b = 0$ in (2), we still cannot get a fit comparable to those obtained with a dipole or a tripole.

However, we found that the inclusion of the second singularity in (2) has a dramatic effect: the χ^2 drops from 661 to 551 for 619 points, nominally a 10 σ effect! More surprisingly, the new singularity has an intercept of 1.39, very close to that obtained in DIS. However, as was already known [7], the new trajectory, which we shall call the hard pomeron, almost decouples from pp and $\bar{p}p$ scattering. Nevertheless, it improves considerably the description of πp and Kp amplitudes, and parametrisation (2) becomes as good as the tripole fit advocated in [8].

The decoupling in pp and $\bar{p}p$ scattering can easily be understood: any sizable coupling will produce a dramatic rise with s, and only pp and $\bar{p}p$ data reach high energy. For these data, the hard pomeron contribution needs to be unitarised (see however [11] for a different opinion). To get a handle on the hard pomeron parameters, it is thus a good idea to fit to lower energies first. We choose to consider the region from 5 to 100 GeV (which includes all the πp and Kp data). We checked that the parameters describing the hard pomeron component are stable if we slightly change the region of interest, by augmenting the minimum energy to *e.g.* 10 GeV, or by decreasing the maximum energy to *e.g.* 40 GeV.

Our best estimate for the hard-pomeron intercept is

$$\alpha_h(t=0) = 1.45 \pm 0.01. \tag{3}$$

However, a new and unexpected hierarchy of couplings is needed. The coupling of the hard pomeron to protons is about three times smaller than that to pions and kaons, and is about 4% of the coupling of the soft pomeron.

The hard pomeron is probably not a simple pole, but it must be close to it: as we obtain the $\gamma\gamma$ cross section via Gribov-Pomeranchuk factorisation, we indeed test the analytic nature of the singularity [10]. The LEP data are compatible with our results, and we prefer a lower value, such as that obtained using PHOJET. Note that the fit of [11], which has a much smaller hard pomeron coupling because the simple-pole structure is used up to the Tevatron, leads to a larger $\gamma\gamma$ cross section, compatible this time with the data unfolded with PYTHIA. Hence our value of the coupling of the hard pomeron to protons must be an upper limit: bigger values would lead to too small a $\gamma\gamma$ cross section, whereas that of [11] would be a lower limit.

To extend our fit to higher energies, one must unitarise the hard pomeron contribution, as it violates the black-disk limit around $\sqrt{s} = 400$ GeV. The way to do this is far from clear, especially as there can be some mixing with the other trajectories. We have shown in [9] that it is possible to find a unitarisation scheme which produces a good description of the data for all energies. The contribution if the hard pomeron is then always smaller than 25% of the total cross section.

In conclusion, several independent analyses point to the fact that a hard pomeron may exist, both in DIS, photoproduction and soft cross sections. This object may be similar to a simple pole for $\sqrt{s} \leq 100$ GeV, and its coupling to protons is small for soft cross sections.

Its contribution is important at large s, large Q^2 or large t. The surprising hierarchy of couplings, as well as their smallness, indicate that our results need confirmation. It may be worth noting here that we obtain similar results if we exclude the ρ data from the analysis. Finally, we must insist on the fact that the combination of two simple poles (a soft and a hard pomeron) is only one of several possibilities. For soft data and DIS data, other models exist [12] which are also compatible with unitarity, and which produce equally good fits. A study of elastic scattering [13] may help distinguish the two-simple-pole model from the tripole and the dipole, as it predicts a contribution with a fast rise but a small slope, which is not natural in the competing models.

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