Brown-HET-1024
TA-530
McGill/95–57

A REVIEW OF THE SOFT POMERON[a]

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Abstract

Soft pomeron fits reproduce all zero-Q^2 data for light quarks, but run into problems at HERA for heavy mesons and for high Q^2, and at the Tevatron for W diffractive production. I review the basic properties of the soft pomeron, and outline the possibilities which have been considered to account for the new data.

1 Light quarks at $Q^2 = 0$:

At high energy, pomeron exchange controls total cross sections, single- and double- diffractive cross sections and elastic cross sections. All these rise very slowly with s, and whatever is responsible for that rise is called the soft pomeron. We shall examine only two of the most extreme models [1, 2] which successfully reproduce the data. All existing models differ by their answers to the following questions:

- *Is the pomeron a Regge trajectory?* One of the most successful models is that of Donnachie and Landshoff (DL) [1], who fit all the soft cross sections

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[c] Supported in part by USDOE contract DE-FG02-91ER 40688-Task A.

using two Regge trajectories: a degenerate one for the ρ (of charge parity $C = -1$) and a ($C = +1$) exchanges, and another for the pomeron. As the center-of-mass energy $\sqrt{s}$ becomes large, and for momentum transfers $t \leq 1$ GeV^2, the pomeron trajectory dominates the hadronic elastic amplitude, which behaves like $s^{1.08+0.25t}$. From such a trajectory, Regge theory predicts the existence of a 2^{++} glueball, with a mass of the order of 1.9 GeV. A glueball candidate has been found precisely at that mass [3].

Note that a simple-pole behaviour is not required to fit the slow increase of the soft cross sections: several other models reproduce it very successfully, and the basic difference leads to the second issue.

• *Unitarisation:* A simple-pole behaviour will eventually break the Froissard bound. Hence, once an amplitude increasing with s faster than a $\log^2 s$ is assumed, one needs to confront the question of unitarisation. As one deals with high-s, eikonal methods are applicable: one can go to impact parameter space, calculate multiple exchanges there, then sum them and go back to t.

Nevertheless, we do not know what the pomeron couples to. If it couples to quarks, then two-pomeron exchange contains more diagrams than the standard eikonal expansion, as multiple exchanges can couple to different quarks. In the DL model [1], at the two-pomeron-exchange level, this leads to a substantial reduction of the coefficient of the eikonal expansion: thus the effect of unitarisation is weak, and brings the one-pomeron intercept to 1.085.

However, the proton can clearly fluctuate into non-elastic states, which eventually recombine into a proton. In an extended eikonal formalism, Capella, Kaidalov, Merino, Pertermann and Tran Thanh Van (CKMPT) [2] find that such fluctuations increase the effect of unitarisation. This enables them to accommodate a larger one-pomeron exchange intercept, of the order of 1.28.

Finally, one may note that it is possible to fit the data with only $\log s$ and $\log^2 s$ terms [4], and hence assume that only the unitarised asymptotic amplitudes matter. It is clear however that some properties of the soft exchanges are lost if unitarisation is strong.

•*Factorisation and quark counting:* One of the main reasons to assume that the pomeron couples to valence quarks is the quark counting rule, which seems to work for pion-proton cross sections, as well as for cross sections involving strange quarks [1]. Hence it seems that quark degrees of freedom are relevant for soft cross sections. Similarly, the amplitudes factorise [5] into one factor associated with the target, one factor associated with the projectile, and a third factor describing the exchange. This implies that the pomeron couples to one quark at a time: otherwise, the exchange would feel the hadronic wave-function, and one would have a convolution that does not factorise. These two properties are violated by perturbative QCD, as well as by strong unitarisation. Nevertheless, our ignorance of hadronic wavefunctions can easily accommodate the existing data, but one has then to assume that the wavefunction of a pion is similar to that of a proton, contrarily to the simplest intuition.

The DL model has received striking confirmation from HERA. The total γp cross section was exactly predicted [1], and the most recent data [6] confirm this fact. Furthermore, one can also calculate photoproduction cross sections: one needs to invent a vertex describing the conversion of a photon into a vector meson, and this vertex controls the magnitude of the cross section. On the other hand, the energy dependence of the cross section entirely comes from the exchanged trajectories (a and pomeron). The DL model can be applied to photoproduction [7], and works perfectly for ρ^0 photoproduction [8, 9]. There are violations of the quark counting rule for Φ, although the observed energy dependence is consistent with a simple-pole parametrisation.

In the case of J/ψ photoproduction [8], it seems however that one encounters the first violation of the simple-pole approach: the cross section rises as $s^{0.4}$. One might question the experimental results, as the prediction holds only in the case of elastic scattering, *i.e.* $\gamma^* p \to \rho^0 p$, without any break-up of the proton. As the proton is not seen, it is hard to assert what the exact background is, and some contamination is possible from $\gamma^* p \to \rho^0 X$. Future runs at HERA will tell us if this is a real effect, as the forward proton has become detectable in the upgraded detectors.

2 Deep Inelastic Scattering

At high Q^2, the simple-pole picture of the soft pomeron seems to break down. There are two instances in which this is manifest.

- *Structure functions:* At small x, F_2 is expected to be dominated by pomeron exchange [10]: as $x \to 0$ the sub-energy flowing through F_2 is $s = \frac{k^2+k_T^2}{x}$, with k^2 the virtuality of the struck quark, and k_T its transverse momentum. Hence at small x the sub-process enters a kinematic range close to that of total cross sections. However, it seems that $Q^2 \neq 0$ introduces a drastic change in behaviour, even for Q^2 as low as 2 GeV^2: the "effective intercept" is of the order of 1.35 [11]. Such a growth of the intercept comes naturally in the CKMPT model [2], as unitarisation weakens when Q^2 increases.

• *Vector Meson Production* The same disagreement can be found in DIS vector meson production [8]. Up to NMC energies, deep-inelastic production of vector mesons (ρ^0 and Φ) is well reproduced by simple-pole models [7], even at high $Q^2 \sim 25$ GeV^2. At HERA, however, DIS production of vector mesons seems to follow the same trend as F_2, and the effective intercept does not seem to be Q^2-dependent.

As there are now several models on the market, it might be worth pointing out in what way they differ. The first one [7] was introduced by Donnachie and Landshoff, who also realised the analogy with lowest-order QCD. This analogy was refined by the present author [12], and remarkable agreement has been obtained both with EMC and NMC data [9]. At lowest-order, the relation between lowest-order ρ^0 production and the gluon structure function is obvious [13]. Ryskin, and later Brodsky et al., [14] have argued that this relation extends to higher orders of perturbation theory. One must realise that this often-quoted result is only approximate: it is a perturbative, leading-log result, which holds at $t = 0$, and which is supposed to relate two non-perturbative quantities. Unfortunately, t cannot be zero in this process, and there has always to be a non-negligible longitudinal momentum transferred to the photon in order for it to convert into a ρ. Hence the equivalent of Bjorken-x is ill-defined, and the relation can only be approximate.

All the above models agree on some of the predictions, namely that the cross section should be dominated by its longitudinal part at large Q^2, and that it should behave like $1/Q^6$ (there might be room for a log Q^2 in the perturbative case). The data from Zeus gives $1/Q^{\left(4.2\pm 0.4^{+1.4}_{-0.5}\right)}$.

3 The pomeron structure function

One way to inquire about the partonic content of the pomeron is to probe it directly. UA8 has shown that hard diffraction does exist [15] and Donnachie and Landshoff predicted a long time ago that some 10% of the hard events at HERA would contain a rapidity gap [16]. In this kind of model [17], the cross section is split into a "pomeron flux factor" and "pomeron structure function".

The first factor comes from the coupling of the pomeron to protons, and the second factor is the analog of the usual proton F_2. A word of caution is in order: as the mass shell of the pomeron is far away, the cross section cannot be continued to a region where the pomeron is on-shell, *i.e.* where its flux is well-defined. Hence the splitting between structure function and flux factor is defined up to a factor, and there is no momentum sum rule for the pomeron structure function. The pomeron flux factor however must behave like $x_P^{-1+2<\alpha(t)>}$, with x_P the fraction of longitudinal momentum carried by the pomeron, and $< \alpha(t) >$ the average pomeron intercept over the t-range of the experiment. For a soft pomeron, one expects [18] $-1 + 2 < \alpha(t) >= 1.11 \pm 0.03$. The HERA data is compatible with this, but is also compatible with a harder behaviour [19].

The pomeron structure function has also been measured [19]. It is worth noting that although such an object can be empirically defined, it is not clear that it is universal, and that the same structure function holds in different processes [20]. From the DL model, one expects a quark structure function $\beta q(\beta) \approx 0.2\beta(1 - \beta)$. There are several determinations which tend to the conclusion that the pomeron is mostly hard, and that it is made of $30 - 80\%$ gluons [15, 19], with a “superhard” component [21], where the pomeron carries all the momentum of the hadron, present in hadronic data.

There is however one major problem: whatever the soft pomeron is made of, it is couples to quarks, and hence its quark structure function cannot be zero-HERA has actually measured it. This seems in blatant contradiction with recent data from CDF [22], who fail to detect W production within a rapidity gap, when a few percent of the total production would be expected in the above picture. This has prompted Goulianos [23] to renormalise the pomeron flux. A less drastic method would be to unitarise the pomeron, and hence to decrease its flux at high energies only. This problem needs to be addressed before meaningful predictions can be made for the LHC.

4 Conclusion

A simple-pole model works perfectly for $x \geq 0.01$, and up to $Q^2 \approx 25$ GeV^2. At smaller x values, there are problems for large quark masses, and for high Q^2.

No model can explain both these facts. Strong unitarisation à la

CKMPT [2] can succeed in fitting the HERA data, but abandons factorisation and quark counting, and cannot account for high-Q^2 data at moderate s. This model predicts that there is a maximum intercept of the order of 1.3. It is of course tempting to see the rise of a perturbative component [24] in the data. However, at present, models mixing a hard pomeron and a soft one [25] do not predict the Q^2 dependence of the data, although they predict an intercept varying with s, with a maximum intercept much larger, of the order of 2.

HERA and CDF data point to the importance of unitarisation, and to the multi-component nature of the pomeron, but we are still far from understanding how to consistently build a model for this.

High-t data will tell us a lot, as they might exhibit the same kind of violation as high-mass and high-Q^2 data. They will directly probe the trajectory of the pomeron, which for glueball exchange should be linear. Besides, the soft pomeron tends to produce distributions which fall rapidly with t, whereas pQCD predicts a much slower fall-off at high t: a weaker t dependence in elastic events would be a signature for a hard pomeron.

Finally, factorization and quark counting are essential to our understanding of the pomeron, and can be tested at HERA, *e.g.* if factorisation holds, the ratio of the diffractive cross section over the elastic one should be the same for J/ψ and for ρ_0, and should be the same at different Q^2. Hence we urge the experimentalists not to throw away their diffractive "background" events!

Acknowledgements

I thank K. Kang and P.V. Landshoff for discussions, and C.A. Pont for a careful proofreading.

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