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An evolving look at Pomeranchuk scattering [1]

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Contents

Abstract. **The evolving way in which high-energy, small-momentum-transfer processes have been described over the past 30 years is briefly reviewed.**

1. Early days (60's)

I learned about Pomeranchuk's ideas [1] about high-energy scattering when I was still a student of Professor Gatto in Florence. The fact that the exchange of vacuum quantum numbers dominated very high energy (a few GeV's in those days!) collisions was very intriguing. It predicted, of course, asymptotic relations such as

$$\sigma_{\mathrm{T}}(\mathrm{pp}) \sim \sigma_{\mathrm{T}}(\mathrm{pn}) \sim \sigma_{\mathrm{T}}(\bar{\mathrm{p}}\mathrm{p}) \sim \ldots , \qquad (1)$$

as well as inequalities

$$\sigma_{\mathrm{el}}(\mathrm{pp}) \sim \sigma_{\mathrm{el}}(\mathrm{pn}) \gg \sigma(\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}), \ \text{etc.} \qquad (2)$$

Those predictions worked fine, but how could we build a more precise model? The answer came with the advent of Regge theory, as exploited by Gribov, Chew, Frautschi, Mandelstam, and others, in the study of high-energy, fixed-momentum-transfer processes.

In this approach, poles in the (t-channel) complex angular momentum J control high energy behaviour. The pole with the largest value of Re J (the so-called leading Regge pole) dominates at sufficiently high energy. The validity of Eqns (1) and (2), together with the approximate constancy of total cross sections, implied that the leading pole had to be at $J \sim 1$ in a t-channel with vacuum quantum numbers, while it had to be lower, say around $J = 1/2$, in non-vacuum channels. The leading vacuum-channel Regge pole was given a name: the Pomeranchukon, soon abbreviated by Gell-Mann to 'the Pomeron'.

Assuming the existence of the Pomeron leads to the approximate constancy of all total and elastic cross sections — something roughly observed at energies around 10 GeV — and to various relations among them from the factorization of Regge-pole residues implied by t-channel unitarity. It soon became clear, however, that cross sections had a tendency to grow with energy: this was first seen at Serpukhov and then definitely shown by the CERN-ISR [2] data at the beginning of the 70s. The simplest Pomeron model could thus be only an approximation and had to be supplemented with more complicated structures in J, such as cuts, whose existence was implied anyway by unitarity.

This led to Gribov's Reggeon Calculus [2], a systematic way to improve on the simplest Regge-pole approximation. Even to this day, adding Gribov's corrections to a 'bare' Pomeron pole slightly above $J = 1$ appears to provide a good description of data up to the highest attainable energies.

2. Duality and dual resonance models (60's – 70's)

In the second half of the 60's the concept of duality entered the strong interaction world through the work of Dolen, Horn and Schmit (DHS) [3]. Quarks had already been introduced, mainly as a book-keeping device for quantum numbers. Quarks and DHS duality were nicely put together by Harari and Rosner [4] in what became known as duality diagrams (see Fig. 1). Even before the introduction of duality diagrams, it had been realized that duality worked in very different ways in non-vacuum and vacuum quantum number channels [5]: while in the former case (Fig. 1a) the exchanged mesonic Regge pole was dual to s-channel resonances, for the latter (Fig. 1b) the Pomeron was dual to a non-resonating background, simply because no (so-called exotic) resonances with the quantum numbers of four quarks and an antiquark are observed. The next question was: could the dominance of the vacuum Regge pole be understood from its unusual duality properties?

In order to answer this question it was necessary to put some 'meat' in the duality diagrams, i.e. to associate some

[1] Talk given on the occasion of receiring the 1999 Pomeranchuk prize, ITEP, Moscow, July 1999. CERN-TH/99-323.

[2] ISR — Intersecting Storage Rings. (*Translator's note.*)

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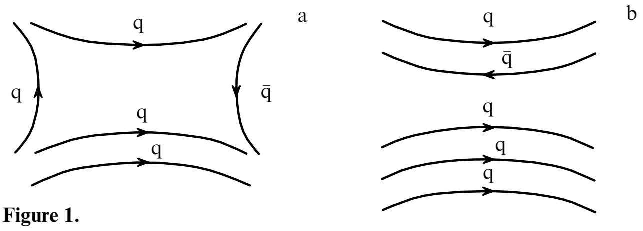

Figure 1.

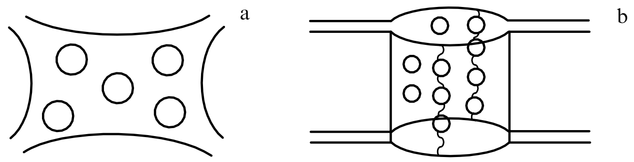

Figure 3.

mathematical expression with them: this is precisely what dual resonance models (DRM) did [6]. As you know, DRMs were later understood as describing the scattering of string-like objects, possibly with quarks at their ends. Let us consider, for simplicity, meson – meson scattering.

The DRM/string reinterpretation of the duality diagrams is simple. In Fig. 2a we see how an s-channel $\mathrm{q}\bar{\mathrm{q}}$ string (obtained from the annihilation of a $\mathrm{q}\bar{\mathrm{q}}$ pair) is dual to a t-channel $\mathrm{q}\bar{\mathrm{q}}$ string, while, in Fig 2b, we see how Pomeranchuk scattering emerges from a non-planar duality diagram. Here, in the s-channel, the two incoming low-mass mesons exchange a quark producing two highly excited strings, while, in the t-channel, after being conveniently stretched (Fig. 2c), the diagram shows closed-string intermediate states. Since closed strings have no ends where quarks can sit, they necessarily have the quantum numbers of the vacuum.

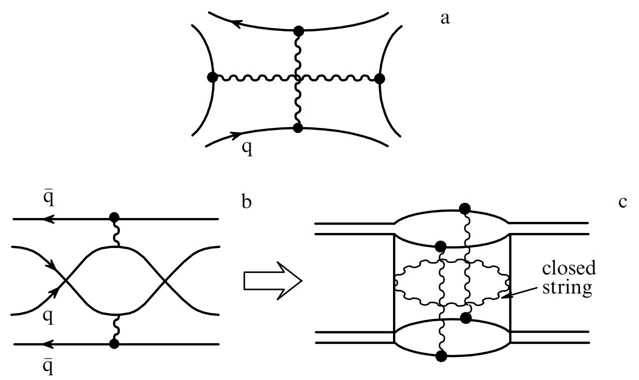

Figure 2.

It was soon realized [7] that, in order to make contact with the real world, the lowest-order diagrams had to be dressed up by adding quark loops. This gives finite width to the resonances, accounts for multiparticle production through the breaking up of long strings into short ones, and, in a word, enforces unitarity. It was also suggested that a physically interesting way to add loops would be one in which, at each order, infinite sets of diagrams of a given topology are added [8]. For instance, the usual meson exchange diagram 2a would be 'improved' to that of Fig. 3a, and would satisfy a planar version of unitarity forcing the leading (ρ-type) Regge trajectory to have an intercept below 1 while remaining degenerate with the f_0 trajectory. Planarity would also imply the absence of cuts in the J-plane.

At the next level of topological complexity we will now find the cylinder-like topology of Fig. 3b, representing the bare-Pomeron (still a pole in J). From an s-channel view-point, the bare Pomeron now appears as the result of two independent multiperipheral cascades originating from two highly excited strings breaking up into shorter strings. As long as correlations between the two cascades can be neglected (as suggested by the topology of the diagrams), the intercept of the so-defined bare-Pomeron trajectory should be close to 1 [9]. More complicated topologies would then lead to Gribov-type corrections.

3. QCD (70's)

With the advent of QCD, duality diagrams get extra flesh in them: gluons. This is shown in Fig. 4 for the planar duality diagram corresponding to $\mathrm{q}\bar{\mathrm{q}}$ exchange. Gluons should be added to the bare duality diagram in such a way as to preserve the planar topology of the original diagram. In 1974 't Hooft pointed out [10] that such a resummation of diagrams topology by topology is automatically enforced if one generalizes QCD to a gauge group $SU(N_{\mathrm{c}})$ and then performs a $1/N_{\mathrm{c}}$ expansion, while keeping $g^2 N_{\mathrm{c}}$ and the number of flavours N_{f} fixed. In this limit, one recovers a neat correspondence between QCD and duality diagrams.

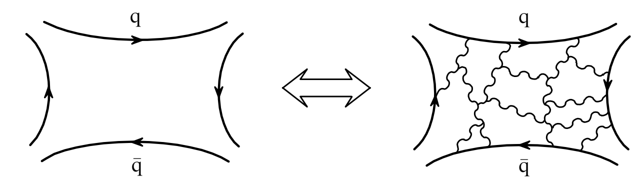

Figure 4.

Soon after, I proposed [11] a generalization of 't Hooft's expansion where, in the large N_{c} limit, $N_{\mathrm{f}}/N_{\mathrm{c}}$ is also kept fixed. In this way, one automatically obtains (see Fig. 5 for the simplest topology) the topological expansion of unitarity corrections discussed in the previous section. Therefore, the bare Pomeron, and the Gribov calculus adding corrections to it, find a very natural place in QCD. The systematic use of these ideas is the basis of the 'dual parton model' of Kaidalov and Ter Martirosyan, and of Capella and Tranh Thanh Van [12]. The expansion parameter of Gribov's calculus, the so-called triple Pomeron vertex, gets identified with $1/N$ (either N_{c} or N_{f}, since they are now of the same order). Yet, the large-

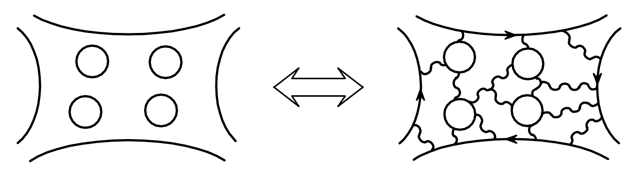

Figure 5.

N expansions correspond to non-perturbative expansions of QCD, which cannot be simply computed. Even today we are still lacking reliable methods to compute even the leading term of the $1/N_c$ (*a fortiori* of the topological) expansion of QCD. This can only be done [13] in the case of two-dimensional QCD, where all the expected properties can be shown to hold true.

I should mention here another possible approach to the QCD Pomeron. It started with the work of Low and Nussinov [14] in 1975, in which Pomeron exchange is simply represented (Fig. 6a) as two-gluon exchange (naturally explaining its quantum numbers and effective angular momentum). The Low–Nussinov Pomeron, however, is not a Regge pole and thus lacks some desirable features. It can be improved along the lines pioneered by Lipatov [15] in which the gluon itself is 'Reggeized' and the exchange of several Reggeized gluons is now identified with the Pomeron (Fig. 6b). I think that, eventually, the Pomeron of the topological expansion and that of the Low–Nussinov–Lipatov approach should be brought together as different effective descriptions of the same object in QCD.

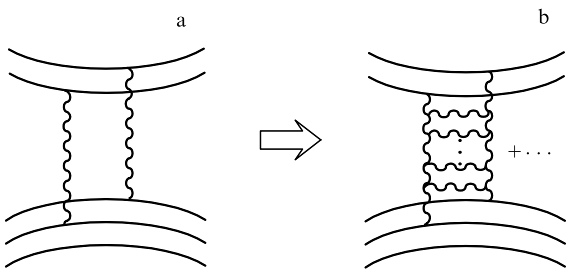

Figure 6.

In the more recent past, especially under the thrust of experiments at HERA [3], people have tried to understand [16] the so-called 'structure' of the Pomeron through the study of hard processes taking place in conjunction with a diffractive signature (e.g. a large rapidity gap, or a leading particle with the same quantum numbers as those of the target). Is the Pomeron basically made of two 'constituent' gluons (as in the simplest Low–Nussinov picture) or is its momentum shared by many wee gluons (as perhaps suggested by Lipatov's extension in the so-called BFKL Pomeron)? And what is the fraction of the Pomeron's momentum carried by quark–antiquark pairs?

Incidentally, Dirk Graudenz and myself [17] recently made the following observation. If the Pomeron is harder in gluons than ordinary hadrons [4] then it may be profitable to search for a light Higgs boson (i.e. one with a 2γ signature) in (semi) diffractive processes at the LHC [5]. Recall that the Higgs boson is expected to be produced mainly by gluon–gluon fusion while the irreducible background is due to $q\bar{q} \to \gamma\gamma$. Enhancing the gluon/quark flux by the diffractive trigger will thus enhance by a similar ratio the signal to background ratio!

[3] ep — collider at the DESY laboratory near Hamburg. (*Translator's note*)
[4] Here it is meant that unlike for the decay of ordinary hadrons, in the decay of a pomeron the gluons take a significant part of the momentum. (*Translator's note*)
[5] LHC — Large Hadron Collider. (*Translator's note*.)

4. The Pomeron in the superstring era (> '84)

Let me first recall that presently studied superstring theories are not expected to have a direct relation to any effective string originating in QCD. With this in mind let us ask: What dominates high energy small momentum transfer scattering in superstring theory? The answer is simple: gravitational scattering! In other words, the Pomeron of superstring theory becomes the graviton Regge trajectory with intercept 2 (rather than 1) and with a bona-fide massless particle (indeed the graviton) lying on it (there are also lower-spin massless partners of the graviton, but they are irrelevant at very high energy).

A very amusing consequence of the radically different spin–mass situation in gravitational and gauge interaction scattering is that the large- and short-distance regimes get somehow swapped [18] as one goes from one case to the other. This is shown in Fig. 7, using an energy-impact parameter phase diagram. We see that perturbative and non-perturbative regimes are interchanged in the two diagrams. Gravitational collapse (which is expected to occur at sufficiently short distance) is the analogue of confinement (which is instead a large-distance phenomenon). The connection could turn out to be deeper than that through use of Maldacena-type dualities [19] between gravitational theories in the bulk and

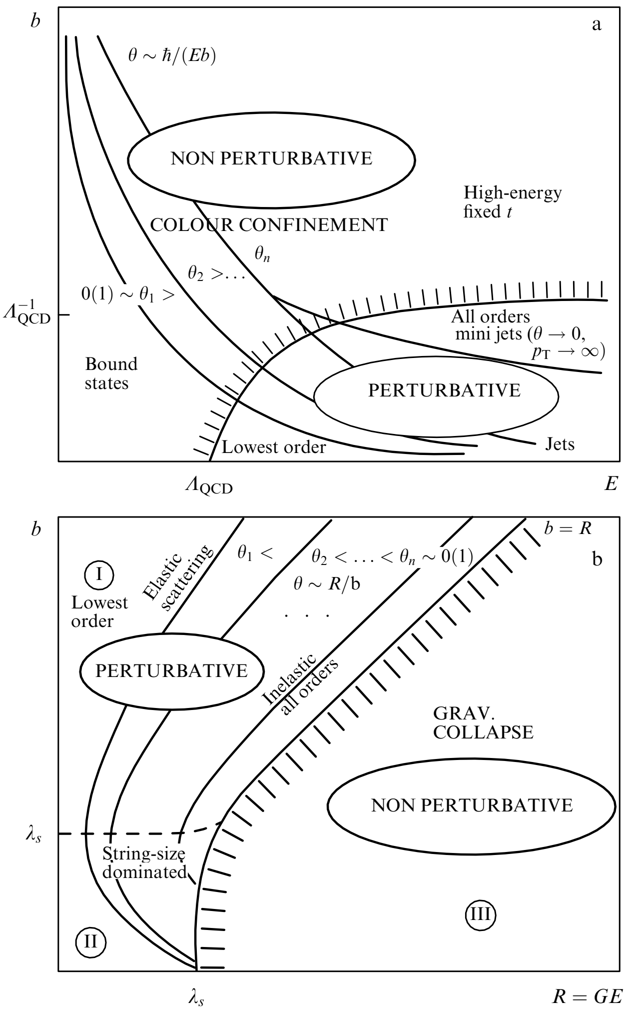

Figure 7.

gauge theories on the boundary: there too an IR – UV connection is seen to emerge.

I will conclude by mentioning the recent suggestion [20] that the 'true' Planck/string scale may actually be much lower than we think, perhaps as low as 10 TeV or so. This lowering of the Planck scale is only possible if gravity lives in a space containing large extra dimensions (perhaps as large as a millimetre), while the standard-model interactions are confined to a subspace, a 'brane', e.g. to our usual four-dimensional space-time. In this case, the interesting new phenomena associated with the gravitational Pomeron, such as black-hole formation and evaporation, will occur at energies that may soon become accessible to accelerator experiments. This would also dramatically lower the energy scale at which Pomeranchuk scattering applies and make superstring theory very relevant — and thus testable — in the near future.

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