POMERON PHYSICS AND QCD

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We review some theoretical ideas concerning diffractive processes. We discuss the Regge Ansatz for the pomeron and the two pomeron model. Then we present the results obtained from nonperturbative QCD for high energy scattering. There we can extract from elastic scattering data the parameters describing the QCD vacuum, in particular the string tension.

1. Introduction

In this contribution to the Ringberg workshop 2003 we shall discuss a topic of hadron physics: diffractive processes at high energies. We speak of a diffractive scattering process if one or more large rapidity gaps occur in the final state. Examples are the reactions (see Fig. 1)

$$\begin{aligned} a + b &\to X + Y, \\ a + b &\to X + Z + Y, \end{aligned} \tag{1}$$

where a, b are the incoming particles and X, Y, Z can be particles or groups of particles. Large rapidity gaps are required between X and Y and X, Y and Z. The object exchanged across the rapidity gaps is called the pomeron (see for instance Ref. 1,2 for the history and many refences).
We can distinguish three classes of reactions involving pomerons.

- Soft reactions, where no large momentum transfers occur and no short distance physics is involved. Examples are the following elastic scattering processes near the forward direction:

$$p + p \to p + p \tag{2}$$

$$\pi + p \to \pi + p \tag{3}$$

$$\gamma + p \to \gamma + p. \tag{4}$$

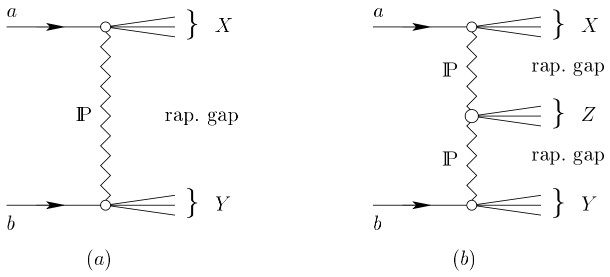

Figure 1. Processes with (a) one and (b) two large rapidity gaps .

In (4) we consider real photons. In all these cases the objects scattering are relatively large, with diameters of order 0.5 to 1.0 fm.

- Semi-hard reactions, where both large and small objects and/or momentum transfers are involved. Examples are

$$p + p \to p + H + p, \tag{5}$$

$$p + p \to p + 2 \text{ high } p_T \text{ jets } + p \tag{6}$$

$$\gamma^* + p \to \gamma^* + p. \tag{7}$$

  Here H denotes the Higgs particle. The virtual photon γ^* in (7) is supposed to have high Q^2, such that it is a small object probing the large proton. The imaginary part of the amplitude of forward virtual Compton scattering (7) is, of course, directly related to the structure functions of deep inelastic scattering. The diffractive central production of high p_T jets (6) was first discussed in Ref. 3 where also the important concept of the partonic structure of the pomeron was introduced.
- Hard reactions, where all participating objects are small and ideally all momentum transfers should be large. The prime example for this is $\gamma^* - \gamma^*$ scattering with highly virtual photons

$$\gamma^* + \gamma^* \to \gamma^* + \gamma^*. \tag{8}$$

  Here the observable quantity is the imaginary part of the forward scattering amplitude, that is the total cross section for $\gamma^*\gamma^*$ going to hadrons

$$\gamma^* + \gamma^* \to X. \tag{9}$$

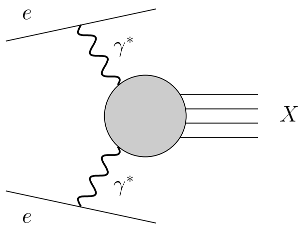

Figure 2. The two photon process in e^+e^- collisions giving hadrons X.

This can be measured for instance at e^+e^- colliders, see Fig. 2.

2. Pomerons: What Are They?

The main question is now: what happens in a diffractive collision at high energy, that is when a pomeron is exchanged? Let us discuss this first for the prototype of such collisions, elastic hadron-hadron scattering: two hadrons come in, they interact, two hadrons go out (Fig. 3a). What happens in between? This question was, of course, already studied before the advent of QCD. As an example of a pre-QCD approach let us discuss Regge theory which is based on general analyticity and crossing properties of scattering

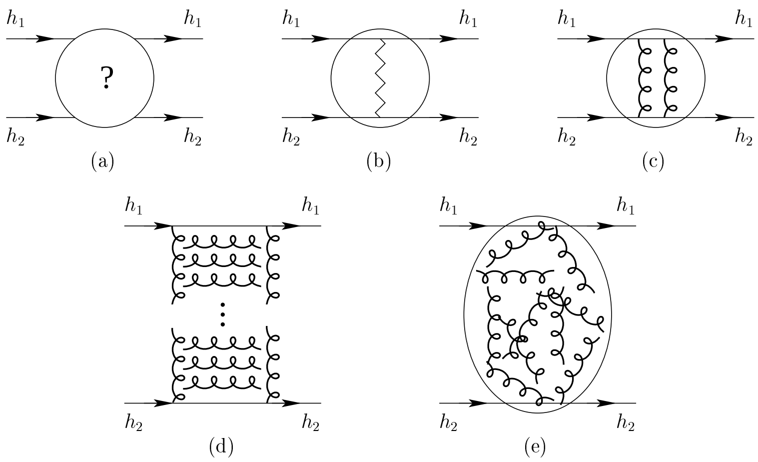

Figure 3. Hadron-hadron scattering: (a) what happens?, (b) phenomenological pomeron and (c) two gluon exchange, (d) exchange of a reggeised gluon ladder and (e) in the fluctuating vacuum gluon field.

amplitudes. The Regge approach was developed in the nineteensixties and the answer provided then to our question was: an object is exchanged, the pomeron (Fig. 3b), which corresponds to the rightmost singularity in the complex angular momentum plane. But to this date Regge theory alone cannot predict if the pomeron is a single Regge pole, consists of two Regge poles, is maybe a Regge cut, and so on. Nevertheless, the assumption that the pomeron seen in elastic hadron-hadron scattering is a simple Regge pole works extremely well phenomenologically.

We discuss as an example the Donnachie-Landshoff (DL) Ansatz [4] for the soft pomeron in Regge theory. The DL pomeron is assumed to be effectively a simple Regge pole. Consider as an example $p-p$ elastic scattering

$$p(p_1) + p(p_2) \to p(p_3) + p(p_4), \tag{10}$$

$$s = (p_1 + p_2)^2, \ t = (p_1 - p_3)^2, \tag{11}$$

where s and t are the c.m. energy squared and the momentum transfer squared. The corresponding diagram is as in Fig. 3b, setting $h_1 = h_2 = p$. In the DL Ansatz the wavy line in Fig. 3b can be interpreted as an effective pomeron propagator given by

$$(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}. \tag{12}$$

Here $\alpha_{\mathbb{P}}(t)$ is the pomeron trajectory which is assumed to be linear in t.

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t \tag{13}$$

with $\alpha_{\mathbb{P}}(0) = 1 + \epsilon_1$ the pomeron intercept and $\alpha'_{\mathbb{P}}$ the slope of the pomeron trajectory. The $pp\mathbb{P}$ vertex, or Regge residue factor, is assumed to have the form

$$-i3\beta_{\mathbb{P}} F_1(t)\gamma^{\mu} \tag{14}$$

where $F_1(t)$ is the isoscalar Dirac electromagnetic form factor of the nucleons and $\beta_{\mathbb{P}}$ the $\mathbb{P}$-quark coupling constant. A good representation of the form factor is given by the dipole formula

$$F_1(t) = \frac{4m_p^2 - 2.79t}{(4m_p^2 - t)(1 - t/m_D^2)^2},$$
$$m_D^2 = 0.71 \text{ GeV}^2. \tag{15}$$

Putting everything together we find from these rules the following expression for the scattering amplitude at large s

$$\langle p(p_3, s_3), p(p_4, s_4)|\mathcal{T}|p(p_1, s_1), p(p_2, s_2)\rangle \sim 2s\big(3\beta_{\mathbb{P}} F_1(t)\big)^2 \delta_{s_3 s_1}\delta_{s_4 s_2} i(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1} \tag{16}$$

Here $s_1, \ldots, s_4$ are the spin indices. This formula (16) describes the data surprisingly well and from the fits one gets the following values for the DL-pomeron parameters:

$$\epsilon_1 = 0.0808, \quad \alpha'_{\mathbb{P}} = 0.25 \text{ GeV}^{-2}, \quad \beta_{\mathbb{P}} = 1.87 \text{ GeV}^{-1}. \tag{17}$$

Examples of the fits are shown in Figs. 4 and 5 where in addition to the pomeron also non-leading Regge exchanges are taken into account. Note in

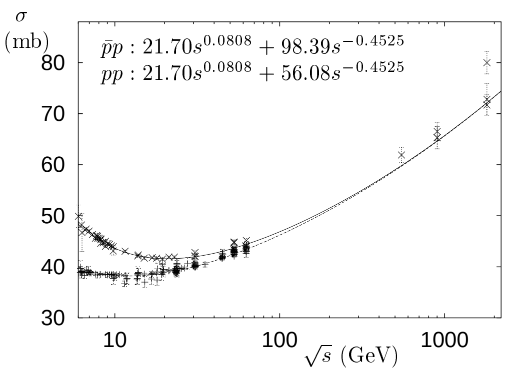

Figure 4. Total pp and $p\bar{p}$ cross sections as function of $\sqrt{s}$ (from Ref. 1).

Fig. 4 that the Tevatron measurements of $\sigma_{tot}(p\bar{p})$ at $\sqrt{s} \simeq 1.8$ TeV give two incompatible values. A resolution of this longstanding discrepancy would be very welcome. The simple DL Ansatz failed, however, when applied to semi-hard diffractive reactions. A second pomeron had to be introduced [5] in order to describe the structure functions of deep inelastic lepton-nucleon scattering, that is the total cross section of a highly virtual photon being absorbed by a proton. This second pomeron, the hard pomeron, was found to have an intercept much higher than the soft one:

$$\alpha_{\mathbb{P}}(0)|_{\text{hard}} = 1 + \epsilon_0, \quad \epsilon_0 \cong 0.44. \tag{18}$$

This, of course, spoiled the simplicity of the original DL-Regge picture for the pomeron and raised a number of questions. Is the hard pomeron also present in pp scattering? Then it should show up at higher energies and maybe the LHC experiments will be able to tell. The biggest question for a theorist is, of course, how to understand all this in the framework of the theory of strong interactions, that is quantum chromodynamics, QCD.

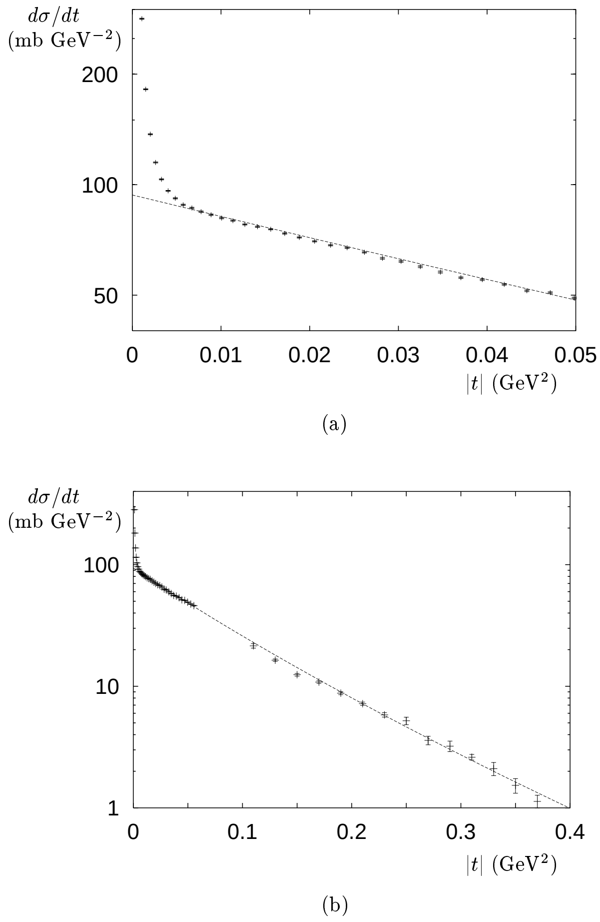

Figure 5. pp elastic scattering at $\sqrt{s} = 53$ GeV (from Ref. 1).

Clearly, the advent of QCD in the early nineteenseventies changed the whole scene in hadronic physics radically. We have since then a quantum field theory where in principle all hadronic phenomena should be derivable from the fundamental Lagrangian. The question arose how to describe the pomeron in QCD. The first answers were given in Ref. 6. These authors modeled the pomeron as a perturbative two-gluon exchange (Fig. 3c). However, this approach has problems. Gluons in QCD are massless particles. Exchanging one of them leads in perturbation theory to a long-range Coulomb potential $\propto 1/r$ and a singularity in $d\sigma/dt$ at $t = 0$. Of course, in elastic hadron-hadron scattering one must exchange at least two gluons due to colour conservation. But this still gives a long-range potential falling with some power of $1/r$ and singularities in derivatives of $d\sigma/dt$ at $t = 0$. From general principles we know the absence of massless hadrons to imply that $d\sigma/dt$ is not singular at $t = 0$. This is, of course, consistent with experiment. The two-gluon exchange is the starting point of the BFKL approach [7,8] where the interaction of the gluons is taken into account. Instead of two gluons, one or even several gluon ladders, where the gluons themselves are "reggeised", are exchanged (Fig. 3d). Even if this is usually called the perturbative pomeron of QCD, one should keep in mind that this pomeron represents a very sophisticated summation of an infinite number of diagrams in perturbation theory. For each diagram only the leading term for high energies is kept. There is no guaranty that the summation of the leading terms really gives the leading term of the full theory. Also, this approach as it is based on perturbation theory does not generate a finite length scale for the potential and thus leads to singularities in derivatives of $d\sigma/dt$ at $t = 0$. But the BFKL pomeron should be important for hard diffractive reactions.

For hadron-hadron scattering the total cross section and the parameters describing $d\sigma/dt$, for instance the slope parameter b,

$$b(s) = \frac{\partial}{\partial t} \ln \frac{d\sigma}{dt}(s,t)|_{t=0}, \tag{19}$$

are dimensioned parameters. This fact suggested to some authors to consider the soft pomeron as a nonperturbative object in QCD, see Refs. 9-12,1 and references therein. We shall treat this point of view in Sec. 3. In this approach hadrons scatter at small $|t|$ since the quarks in the hadrons feel the nonperturbative fluctuations of the gluon fields in the vacuum (Fig. 3e). These fluctuations are assumed to be of Gaussian nature in the stochastic vacuum model [13]. We will show that the application of this model to high energy scattering allows us to extract from high energy data on $d\sigma/dt$ values for the vacuum parameters, the gluon condensate, the correlation length, the non-abelian parameter and related to them the string tension. As we shall see, the results compare well to lattice calculations and other information on these parameters.

3. Soft Hadron Reactions

In this section we will outline a microscopic approach towards hadron-hadron diffractive scattering (see Refs. 10-12). Consider as an example elastic scattering of two hadrons h_1, h_2

$$h_1 + h_2 \rightarrow h_1 + h_2 \tag{20}$$

at high energies and small momentum transfer. We will look at reaction (20) from the point of view of an observer living in the "femto-universe", that is we imagine having a microscope with resolution much better than 1 fm for observing what happens during the collision. Of course, we should choose an appropriate resolution for our microscope. If we choose the resolution much too good, we will see too many details of the internal structure of the hadrons which are irrelevant for the reaction considered and we will miss the essential features. The same is true if the resolution is too poor. In [10] we used a series of simple arguments based on the uncertainty relation to estimate this appropriate resolution. Let $t = 0$ be the nominal collision time of the hadrons in (20) in the c.m. system. This is the time when the hadrons h_1 and h_2 have maximal spatial overlap. Let furthermore be $t_0/2$ the time when, in an inelastic collision, the first produced hadrons appear. We estimate $t_0 \approx 2$ fm from the Lund model of particle production [14]. Then the appropriate resolution, that is the cutoff in transverse parton momenta k_T of the hadronic wave functions to be chosen for describing reaction (20) in an economical way is

$$k_T^2 \leq \sqrt{s}/(2t_0) \tag{21}$$

where $\sqrt{s}$ is the c.m. energy. Modes with higher k_T can be assumed to be integrated out. With this we could argue that over the time interval

$$-\frac{1}{2}t_0 \leq t \leq \frac{1}{2}t_0 \tag{22}$$

the following should hold:

(a) The parton state of the hadrons does not change qualitatively, that is parton annihilation and production processes can be neglected for this time.
(b) Partons travel in essence on straight lightlike world lines.
(c) The partons undergo "soft" elastic scattering.

The strategy is now to study first soft parton-parton scattering in the femto-universe. There, the relevant interaction turns out to be mediated by the gluonic vacuum fluctuations. It is common belief that these have a highly nonperturbative character. In this way the nonperturbative QCD vacuum structure enters the picture for high energy soft hadronic reactions. Once we have solved the problem of parton-parton scattering we have to fold the partonic S-matrix with the hadronic wave functions of the appropriate resolution (21) to get the hadronic S-matrix elements.

Here we can only give an outline of the various steps in this program. Let us start by considering meson-meson scattering:

$$M_1(P_1) + M_2(P_2) \to M_1(P_3) + M_2(P_4). \tag{23}$$

We represent mesons as $q\bar{q}$ dipoles. We use standard techniques of quantum field theory, the LSZ reduction formula and the functional integral. This allows us in a first step to represent the amplitude for the scattering of a $q\bar{q}$ colour dipole on another $q\bar{q}$ dipole at high energies in terms of a correlation function of two lightlike Wegner-Wilson loops (Fig. 6). The second step

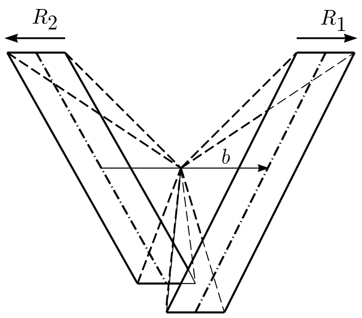

Figure 6. Lightlike Wegner-Wilson loops in Minowski space. The sides of the loops are given by the paths of quarks and antiquarks of the colour dipoles of sizes $\vec{x}_T = \vec{R}_1$ and $\vec{y}_T = \vec{R}_2$. The impact parameter is b (from Ref. 1).

is to fold with the meson wave functions which describe the distribution of the colour dipoles in the mesons. The final formula reads

$$\begin{aligned} S_{fi} &= \delta_{fi} + i(2\pi)^4 \delta(P_3 + P_4 - P_1 - P_2) T_{fi}, \\ T_{fi} &\equiv \langle M_1(P_3), M_2(P_4) | \mathcal{T} | M_1(P_1), M_2(P_2) \rangle \\ &= -2is \int \mathrm{d}^2 b_T \mathrm{d}^2 x_T \mathrm{d}^2 y_T e^{i\vec{q}_T \cdot \vec{b}_T} w_1(\vec{x}_T) w_2(\vec{y}_T) \\ &\qquad \times \langle \mathcal{W}_+(\frac{1}{2}\vec{b}_T, \vec{x}_T) \mathcal{W}_-(-\frac{1}{2}\vec{b}_T, \vec{y}_T) - 1 \rangle_G. \end{aligned} \tag{24}$$

Here $s = (P_1 + P_2)^2$ is the c.m. energy squared and $\vec{q}_T$ is the momentum transfer, which is purely transverse in the high energy limit:

$$\vec{q}_T = (\vec{P}_1 - \vec{P}_3)_T \tag{25}$$

and $\bar{b}_T$ is the impact parameter. Furthermore $\vec{x}_T, \vec{y_T}$ are the transverse sizes of the colour dipoles and $w_{1,2}$ describe the distribution of the colour dipoles in the mesons $M_{1,2}$. The symbol $\langle\ \rangle_G$ denotes the functional integration over the gluonic degrees of freedom and $\mathcal{W}$ are the Wegner-Wilson loops.

The task is now to evaluate the functional integral $\langle\rangle_G$ in (24). Surely we do not want to make a perturbative expansion there, remembering our argument of Sec. 2. Instead, we will turn to the stochastic vacuum model (SVM) introduced in Ref. 13 which provides a method to calculate in a certain approximation functional integrals in the nonperturbative domain of QCD. In the SVM the QCD vacuum is described by three parameters

- G_2, the gluon condensate introduced in Ref. 15,
- κ, the nonabelian parameter,
- a, the vacuum correlation length.

The SVM relates these parameters to the string tension

$$\sigma = \frac{32\pi\kappa G_2 a^2}{81}. \tag{26}$$

The SVM has been applied extensively in low energy hadron physics with considerable success, see Ref. 16 for a review. The QCD vacuum structure has also been investigated in lattice calculations [17,18]. In these one finds the values for the vacuum parameters shown in the second column of Table 1 where the value for the string tension is the input parameter. In the third column of the table the vacuum parameters of the lattice results are used as input and the resulting string tension is calculated from the SVM relation (26). The outcome, $\sqrt{\sigma} = 415$ MeV, is very satisfactory and gives confidence that the SVM catches some true features of the QCD vacuum.

Now we come back to high energy scattering. To evaluate the correlation function of the two lightlike Wegner-Wilson loops in (24) the SVM was continued from Euclidean space, where it was originally formulated, to Minkowski space [11]. This opened the possibility for many applications, see for instance, Ref. 19. Here I can just cite some results as examples.

The differential cross section for proton-proton elastic scattering for $|t| \lesssim 1$ GeV^2 was calculated in Ref. 20. The proton was considered as a quark-diquark system. Thus the simple formula (24) for meson-meson scattering could be taken over with the diquarks replacing the antiquarks. The dipoles in the proton were assumed to have a Gaussian distribution where the parameters can be related [21] to those of the electromagnetic form factors. The data could then be described reasonably well with the

Table 1. Summary of the vacuum parameters G_2: the gluon condensate, κ: the nonabelian parameter, a: the correlation length, and of the string tension σ, as determined with different methods. Quantities which are underlined are input values. In the second column we list the result of the lattice calculations [18], where σ is taken as input. In the third column the result of the string tension in the SVM is listed, where the vacuum parameters G_2, κ, a are input, see (26). The fourth column lists the results for σ, κ, a obtained in Ref. 20 from the data on high energy proton-proton elastic scattering. Here the value of G_2 is calculated using the SVM relation (26). Errors of the numbers can be estimated to be around 10 %.

parameter	lattice calculation quenched	SVM static pot.	high energy scattering
$\sqrt{\sigma}$/MeV	$\underline{420}$	415	435
$G_2^{1/4}$/MeV	486	$\underline{486}$	529
κ	0.89	$\underline{0.89}$	0.74
a/fm	0.33	$\underline{0.33}$	0.32

values for the vaccum parameters listed in column 4 of the table, see Fig. 7. Note that the data extends over many orders of magnitude. It was found in Ref. 20 that the shape of this t-distribution was quite sensitive to the vacuum parameters, in particular to κ.

We see from the table that the vacuum parameters extracted from high-energy scattering are very well compatible with the values obtained from the lattice calculations. In particular, the value for the square root of the string tension $\sqrt{\sigma} = 435$ MeV is well in the range obtained from the study of heavy charmonium states. There one finds $\sqrt{\sigma} \simeq 420 - 440$ MeV. In our opinion this gives support to the idea that high energy hadron-hadron scattering is dominated by nonperturbative QCD effects.

But maybe pp is special. Let us therefore look at one other result of this approach. In Fig. 8 we show the pomeron contributions to various hadron-hadron total cross sections at $\sqrt{s} = 20$ GeV as function of the hadron size parameter R_h divided by R_p. The curve, normalised to the pp point, gives the predicted functional dependence. Again, the results are quite satisfactory.

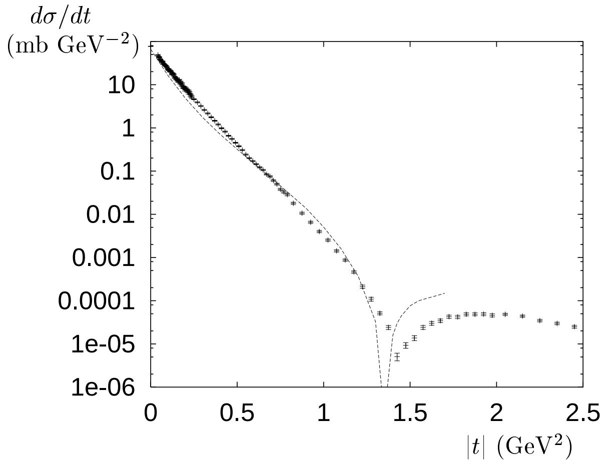

Figure 7. Results from [20] for the elastic differential cross section for proton-proton scattering at $\sqrt{s} = 23$ GeV using the matrix cumulant expansion method (dashed line) compared to the experimental data (from Ref. 1).

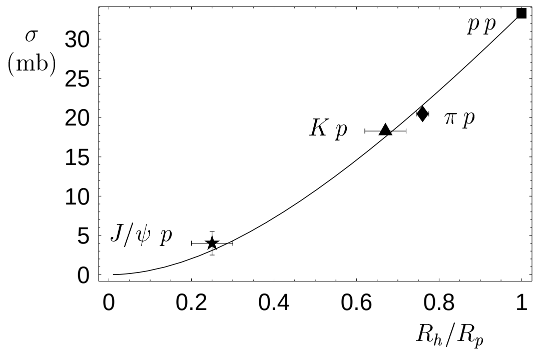

Figure 8. The pomeron contribution at $\sqrt{s} = 20$ GeV to hadron-proton total cross sections as function of the hadron size (from Ref. 1).

4. Conclusions

Here we list some points which we consider important in the study of the pomeron in QCD.

- The phenomenological description in terms of the Regge pole Ansatz works surprisingly well. The challenge is to understand / derive this from QCD.

- The soft pomeron and QCD: We have developed a calculational framework based on quantum field theoretic methods. We suggest that the soft pomeron is related to nonperturbative features of QCD, in particular to the QCD vacuum structure. The vacuum parameters like the string tension and the gluon condensate can be quantitatively extracted from high energy scattering data.
- Semi-hard diffractive phenomena, in particular the structure functions of deep inelastic lepton-nucleon scattering are well described for instance by the two pomeron model of Donnachie and Landshoff. Is this directly related to the usual DGLAP evolution as suggested in Ref. 22? What is the role of the BFKL, that is the perturbative, pomeron there? Is there saturation? Why does the dipole picture (see Refs. 23,24,1 and the references therein) work so well? Is there a chance to make nonperturbative calculations for the structure functions at small x from first principles? Some steps in this direction have been presented in Refs. 25,26. For hard pomeron phenomena like the total cross section for $\gamma^* + \gamma^* \to$ hadrons presumably the BFKL approach should work. But there are problems of large higher order corrections [27]. The experimental data [28] from the LEP experiments does not give evidence for the BFKL pomeron, so far.
- What and where is the odderon, the $C = -1$ partner of the pomeron? See Refs. 1,29 for a discussion of this question. Experimental efforts [30] to look for the odderon should be continued and extended.

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