Description of LHC data in a soft interaction model.

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Abstract: We show in this paper that we have found a set of parameters in our model for the soft interactions at high energy, that successfully describes all high energy experimental data, including the LHC data. This model is based on a single Pomeron with large intercept $\Delta_{IP} = 0.23$ and slope $\alpha'_{IP} = 0$, that describes both long and short distance processes. It also provides a natural matching with perturbative QCD. All features of our model are similar to the expectations of N=4 SYM, which at present is the only theory that is able to treat strong interactions on a theoretical basis.

Keywords: Soft Pomeron, BFKL Pomeron, Diffractive Cross Sections, N=4 SYM

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1. Introduction

It is well known that a comprehensive theory of strong interactions is still in an embryonic stage, as we understand little about non-perturbative QCD. On the other hand, considerable progress has been made in building models for soft scattering at high energies [1–5]. The main constituent of these models is the soft Pomeron with a relatively large intercept \( \Delta_P = \alpha_P - 1 = 0.2 - 0.4 \), and exceedingly small slope \( \alpha_P' \simeq 0.02 \text{GeV}^{-2} \). A Pomeron with these characteristics appears in N=4 SYM [6–10] with a large coupling, which, at the moment, is the only theory that allows us to treat the strong interaction on a theoretical basis. Having \( \alpha_P' \to 0 \), the Pomeron in these models has a natural matching with the hard Pomeron that evolves from perturbative QCD. Hence, these models could be a first step in building a self-consistent theoretical description of soft interactions at high energy, in spite, of the many phenomenological parameters (of the order of 10-15) appearing in these models.

The new LHC data on soft interaction scattering at high energy (see Refs. [11–14]) shows that this hope was premature. Indeed, all of the models [1–5] failed to describe the LHC data. At first sight, this
suggests the need for a comprehensive revision of the main ingredients of the Pomeron models applied to high energy soft interactions.

However, an alternate approach is to adjust the Pomeron model’s parameters. Our first attempt to do this was published in Ref. [15], in which we concluded: "In spite of the fact that the values of the parameters, extracted from our current fitting, are slightly different from our previous values, the overall picture remains unchanged. Our updated total and elastic cross sections are slightly lower than the published TOTEM values [14], but still within the relatively large experimental error bars. Should future LHC measurements confirm the present TOTEM values, we will need to revise our dynamic picture for soft scattering."

In the present paper we retract the above statement, as we find that the above conclusion was premature. The set of parameters in our previous paper was found by fitting all data with energy $W \geq 500 GeV$, including the LHC data. In the present version of our GLM model we made no changes other than tuning the 3 Pomeron parameters. Our tuned $\Delta FP$ changes from 0.21 to 0.23, while $GFP$ and $\gamma$, the Pomeron-proton vertices, are unchanged. The small change in the value of $\Delta FP$ is sufficient to produce the desired results in our $\sigma_{tot}$ and $\sigma_{el}$ output values for LHC energies, while the changes in the output values of the other observables are small enough not to spoil the good reproduction of the data achieved in Ref. [15].

Relying on our model that describes all available data, we also include in this paper predictions for LHC higher energies ($W = 8 TeV$ and $W = 14 TeV$). As there has been a recent renewal of interest in cross sections emanating from cosmic ray data [22], we also list our results for $W = 57 TeV$.

2. Our Model

To make our presentation self-contained we give a brief overview of our model, in spite of the fact, that all the ingredients and formulae have been published (see Ref. [1, 2, 15]).

2.1 Two channel model

To account for diffraction dissociation in the states with masses that are much smaller than the initial energy, we use the simple two channel Good-Walker model. In this model we introduce two eigenwave functions, $\psi_1$ and $\psi_2$, which diagonalize the 2x2 interaction matrix $T$,

$$A_{i,k} = <\psi_i | T | \psi_k> = A_{i,k} \delta_{i,i'} \delta_{k,k'}.$$  \hspace{1cm} (2.1)

The two observed states are an hadron whose wave function we denote by $\psi_h$, and a diffractive state with a wave function $\psi_D$. These two observed states can be written in the form

$$\psi_h = \alpha \psi_1 + \beta \psi_2, \quad \psi_D = -\beta \psi_1 + \alpha \psi_2,$$ \hspace{1cm} (2.2)

where, $\alpha^2 + \beta^2 = 1$
2.2 Eikonal approach

Using Eq. (2.1), we can rewrite the s-channel unitarity constraints in the form

\[ 2 \text{Im} A_{i,k}(s,b) = |A_{i,k}(s,b)|^2 + G_{i,k}^{\text{in}}(s,b), \]  

(2.3)

where, \( G_{i,k}^{\text{in}} \) denotes the contribution of all non GW inelastic processes.

In a general solution of Eq. (2.3)

\[ A_{i,k}(s,b) = i \left( 1 - \exp \left( -\frac{\Omega_{i,k}(s,b)}{2} \right) \right), \]  

(2.4)

\[ G_{i,k}^{\text{in}}(s,b) = 1 - \exp \left( -\Omega_{i,k}(s,b) \right), \]  

(2.5)

in which \( \Omega_{i,k} \) are arbitrary. In the eikonal approximation \( \Omega_{i,k} \) are taken as being real. In our model we choose \( \Omega_{i,k} \) as the contribution of a single Pomeron exchange (see Eq. (2.7)).

From Eq. (2.3) we deduce that the probability that the initial state \((i,k)\) remains intact during the interaction, is \( P_{i,k}^S = \exp \left( -\Omega_{i,k}(s,b) \right) \).

It should be stress that in this model we describe the variety of states produced with different masses and other quantum numbers, in diffraction dissociation, by a single state \((\psi_D)\) with unknown mass. Using Eq. (2.1), Eq. (2.2) and Eq. (2.7) we obtain that one Pomeron exchange has the following contributions to the different processes:

- Elastic scattering: \( p + p \to p + p \) \hspace{1cm} \( A_{p,p} = \alpha^4 A_{1,1} + 2\alpha^2 \beta^2 A_{1,2} + \beta^4 A_{2,2} \);
- Single diffraction: \( p + p \to D + p \) \hspace{1cm} \( A_{p,D} = \alpha \beta (\alpha^2 A_{1,1} + (\alpha^2 - \beta^2) A_{1,2} + \beta^2 A_{2,2}) \);
- Double diffraction: \( p + p \to D + D \) \hspace{1cm} \( A_{D,D} = \alpha^2 \beta^2 (A_{1,1} - 2 A_{1,2} + A_{2,2}) \);  

(2.6)

Eq. (2.6) shows the particular realization of the Good-Walker mechanism [16] for diffraction production, in the two channel model. It is worthwhile mentioning that this mechanism is the only source of diffraction in N=4 SYM, due to AdS-CFT correspondence (see for example Ref. [10]).

2.3 Pomeron

As we have mentioned, our basic ingredient is the soft Pomeron, which has the following contribution to the elastic scattering amplitude for the process: \( i + k \to i + k \) where \( i \) and \( k \) are the states that are described by the wave functions \( \psi_i \) and \( \psi_k \)

\[ \Omega_{i,k}(s,b) = g_i(b) g_k(b) P(s). \]  

(2.7)

\( P(s) = s^\Delta \), and \( g_i(b) \) and \( g_k(b) \) are the Pomeron-hadron vertices parameterized in the form:

\[ g_l(b) = g_l S_l(b) = \frac{g_l}{4\pi} m_l^3 b K_1 (m_l b). \]  

(2.8)
\( S_l(b) \) is the Fourier transform of \( \frac{1}{(1+q^2/m_l^2)} \), where, \( q \) is the transverse momentum carried by the Pomeron, \( L=1,2 \).

The form of \( P(s) \) that we use, corresponds to a Pomeron trajectory slope \( \alpha'_P = 0 \). This is compatible with the exceedingly small fitted value of \( \alpha'_P \), and in accord with N=4 SYM [6].

\( \Omega_{i,k} \) is the imaginary part of the scattering amplitude for a single Pomeron exchange.

### 2.4 Pomeron interactions

In the case of \( \Delta_P \to 0 \), we know that the Pomeron interaction leads to a new source of diffraction production with large mass \( (M \propto s) \), which cannot be described by the Good-Walker mechanism. For \( \Delta_P > 0 \), the Pomeron interaction is responsible for diffraction production of finite (independent of the total energy) mass: \( \log (M^2/s) \propto 1/\Delta_P \). This source can be treated in the same manner as the Good-Walker mechanism (see Ref. [17]). We believe that we need to account for the Pomeron interaction separately, since the typical diffractive mass depends on the Pomeron intercept, and this effect needs to be taken into account in the fitting procedure.

Taking \( \alpha'_P = 0 \), allows us to sum all diagrams having Pomeron interactions [1, 2]. This is the great advantage of such an approach. In our model we only take into account triple Pomeron interaction vertices \( (G_{3P}) \), this provides a natural matching to the hard Pomeron, since at short distances \( G_{3P} \propto \alpha^2_P \), while other vertices are much smaller. For a thorough description of the procedure for summing all diagrams, we refer to our papers (see Refs. [1, 2, 15]).

**Enhanced diagrams:** In our model [2], the Pomeron’s Green function that includes all enhanced diagrams, is approximated using the MPSI procedure [18], in which a multi Pomeron interaction (taking into account only triple Pomeron vertices) is approximated by large Pomeron loops of rapidity size of \( \ln s \).

We obtain

\[
G_P(Y) = 1 - \exp \left( \frac{1}{T(Y)} \right) \frac{1}{T(Y)} \Gamma \left( 0, \frac{1}{T(Y)} \right),
\]

in which:

\[
T(Y) = \gamma e^{\Delta_P Y}.
\]

\( \Gamma (0, 1/T) \) is the incomplete gamma function (see formulae 8.35 in Ref. [19]).

**Semi-enhanced (net) diagrams:** A brief glance at the values of the parameters of our model (see Ref. [15]), shows that we have a new small parameter, namely, \( G_{3P}^2 P(s) \ll 1 \), while \( G_{3P} g_i P(s) \approx 1 \). We call the diagrams which are proportional to \( (G_{3P} g_i P(s)) \), but do not contain any of \( G_{3P}^2 P(s) \) contributions, net diagrams. Summing the net diagrams [1], we obtain the following expression for \( \Omega_{i,k}(s,b) \):

\[
\Omega_{i,k}^{1,k}(Y; b) = \int d^2 b' \frac{g_i(b') g_k(b' - \bar{b}) \left( 1/\gamma G_{P} (T(Y)) \right)}{1 + (G_{3P}/\gamma) G_{P}(T(Y)) \left[ g_i(b') + g_k(b' - \bar{b}) \right]}.
\]

(2.11)

\( G_{3P} \) is the triple Pomeron vertex, and \( \gamma^2 = \int \frac{d^2 k}{4\pi^2} G_{3P}^2 \).
2.5 Final formulae

For the elastic amplitude we have:

\[ a_{el}(b) = i (\alpha^4 A_{1,1} + 2\alpha^2 \beta^2 A_{1,2} + \beta^4 A_{2,2}) . \]  

(2.12)

For diffraction production we introduce an additional contribution due to the Pomeron interaction, which we call non-Good-Walker (non-GW). For single diffraction we have (see Ref. [15]):

\[ A_{sd}^{el} + A_{sd}^{nc} = \int d^2b \, 2 \Delta \left( \frac{G_{3P}}{\gamma} \right) g_i \left( \vec{b} - \vec{b}', m_i \right) g_l \left( \vec{b}', m_l \right) g_k \left( \vec{b}', m_k \right) \times \]

\[ Q \left( g_i, m_i, \vec{b} - \vec{b}', Y_m \right) Q \left( g_{mk}, m_{k}, \vec{b}', Y - Y_m \right) Q \left( g_{mi}, \vec{b}', Y - Y_m \right) , \]  

(2.13)

where,

\[ Q(g, m, b; Y) = \frac{G_{P}(Y)}{1 + (G_{3P}/\gamma) \, g \, G_{P}(Y) \, S(b, m)} . \]  

(2.14)

For double diffraction we have:

\[ r \tilde{A}_{sd}^{dl} = \int d^2b' \, 4 \left( \vec{b} - \vec{b}', m_i \right) g_k \left( \vec{b}', m_k \right) \times \]

\[ Q \left( g_i, m_i, \vec{b} - \vec{b}', Y - Y_1 \right) e^{2\Delta \delta Y} Q \left( g_{mk}, m_{k}, \vec{b}', Y_1 - \delta Y \right) . \]  

(2.15)

Eq. (2.13) and Eq. (2.15) are the simplifications of the exact formulae of Ref. [1]. We have checked that they approach the values of the exact formulae reasonably well, within 5 – 10%.

For single diffraction, \( Y = \ln \left( M^2 / s_0 \right) \), where, \( M \) is the SD mass. For double diffraction, \( Y - Y_1 = \ln \left( M_1^2 / s_0 \right) \) and \( Y_1 - \delta Y = \ln \left( M_2^2 / s_0 \right) \), where \( M_1 \) and \( M_2 \) are the masses of the two bunches of hadrons produced in double diffraction. \( s_0 \) is the minimal produced mass, which is about 1 GeV. The integrated cross section of the SD channel is written as a sum of two terms: the GW term, which is equal to

\[ \sigma_{sd}^{GW} = \int d^2b \left\{ \alpha \beta \left\{ -\alpha \alpha^2 A_{1,1} + (\alpha^2 - \beta^2) A_{1,2} + \beta^2 A_{2,2} \right\} \right\}^2 . \]  

(2.16)

The second term describes diffraction production due to non-GW mechanism:

\[ \sigma_{sd}^{nGW} = 2 \int dY_m \int d^2b \]

\[ \left\{ \alpha^6 A_{1,1,1}^{sd} e^{-\Omega_1(1)}(Y;b) + \alpha^2 \beta^4 A_{1,2,2}^{sd} e^{-\Omega_1(2)}(Y;b) + 2 \alpha^4 \beta^2 A_{1,1,2}^{sd} e^{-\frac{1}{2}(\Omega_1(1) + \Omega_1(2))}(Y;b) \right\} . \]  

(2.17)

The cross section of the double diffractive production is also a sum of the GW contribution,

\[ \sigma_{sd}^{GW} = \int d^2b \alpha^2 \beta^2 \left\{ A_{1,1} - 2 A_{1,2} + A_{2,2} \right\}^2 , \]  

(2.18)
to which we add the term which is determined by the non GW contribution,

\[
\sigma_{dd}^{n\text{GW}} = \int d^2b \left\{ \alpha^4 A_{1,1}^{dd} e^{-\Omega_{1,1}(Y:b)} + 2\alpha^2 \beta^2 A_{1,2}^{dd} e^{-\Omega_{1,2}(Y:b)} + \beta^4 A_{2,2}^{dd} e^{-\Omega_{2,2}(Y:b)} \right\} \quad \text{(2.19)}
\]

In our model, the GW sector contributes to both low and high diffracted mass, while the non-GW sector contributes only to high mass diffraction \(\log \left( M^2 / s_0 \right) \approx 1/\Delta_{P} \).

3. Results

The output of our current model is presented in Fig. 1, in which we display our calculated cross sections and forward elastic slope. It is interesting to compare the quality of our present results with our previous output [15]. Recall that the two fits have almost identical values for the free parameters, with a single change of \(\Delta_{P} \) from 0.21 to 0.23.

We list the main features of our results:

- The main feature of our present calculation is the excellent reproduction of TOTEM’s values for \(\sigma_{\text{tot}} \) and \(\sigma_{\text{el}} \). The quality of our good fit to \(B_{el} \) is maintained. As regards \(\sigma_{\text{inel}} \), our results are in accord with the higher values obtained by ALICE [11] and TOTEM [14]; ATLAS [12] and CMS [13] quote lower values with large extrapolation errors. We refer the reader to [25] who suggests that the lower values found by ATLAS and CMS maybe due to the simplified Monte Carlo that they used to estimate their diffractive background.

- The quality of our output at lower energies, when compared with ISR data, is not as good as our previous results [3], but still acceptable. Recall that Reggeon exchange, which is included in our model, plays an important role at the low energy end of our data, and a negligible role at higher energies. As our main goal is to provide a good description of the LHC data, we have not tuned the Reggeon parameters, which could lead to an improved characterization of the ISR measurements.

- An interesting observation is that our updated output strongly supports the CDF total and elastic cross sections rather than the E710 values. This is a common feature of other models [4, 21], that have succeeded in reproducing the TOTEM results by making a radical change in their modellings.

- Note that our model is the only one which offers a good reproduction of ISR diffraction, and a reproduction of the diffractive cross sections at higher energies.

- Our reproduction of SD and DD cross sections is complicated by the lack of common definitions of signatures and mass bounds on the diffractive components. All models on the market have introduced at least two different mechanisms to describe diffraction production. In our model these two mechanisms are: the Good-Walker production of the diffraction state with finite unspecified mass (independent of energy and of the values of the parameters in our model); and the diffraction due to Pomeron interactions where the typical mass depends on \(\Delta_{P} \), and which we call non Good-Walker mechanism. In other models (see Refs. [3–5]) the two different mechanisms are called: low mass
diffraction and high mass diffraction. It is assumed that the diffractive production of mass less than $M_0 \approx 2 - 3 \text{GeV}$ stems from Good-Walker mechanism, while the production of masses larger than $M_0$ is due to the Pomeron interaction. This partition appears natural in the case where $\Delta \gamma_0 \rightarrow 0,$ when the Pomeron interaction is responsible for diffractive production in the region where the mass increases with energy. However, for $\Delta \gamma_0 \neq 0$ both mechanisms lead to the production of final states with typical masses, and therefore the artificial requirement that the Good-Walker mechanism produces masses less than $M_0,$ appears unnatural. In our approach we do not specify the value of the mass in the Good-Walker mechanism, but it is certainly larger than $M_0 = 2 - 3 \text{GeV}$. As the Pomeron interaction gives a negligible contribution at $W = 900 \text{GeV}$, we estimate that our typical mass for the GW mechanism is about $10 - 20 \text{GeV}$. Such a large mass for the GW contribution, explains why our Pomeron interaction leads to a small contribution to the cross section for diffraction production due to Pomeron interactions. Note that the experimental errors on the diffractive cross sections are relatively large, and thus the data does not provide a good enough resolution to differentiate between competing models.

- Our calculated $d\sigma_{el} (t \leq 0.55 \text{GeV}^2)/dt$ is presented in Fig.2 together with the corresponding data. The quality of the fit is very good in this region of $t$. It shows that the impact parameter dependence of the model does not change considerably and reproduces the experimental data as well, as in our previous version of the model. We refrain from trying to reproduce the diffractive dip and higher $t$ cross sections since our model is confined to the forward cone.

- Table 1 summarizes our calculated cross sections and $B_{el}$ at 1.8 - 57 TeV. The table provides the predicted values of the cross sections and forward slope at 8, 14 and 57 TeV. Note that the table indicates a slow approach of our predicted elastic amplitude to saturation. A common signature for saturation is $\sigma_{el} = \sigma_{inel} = 0.5 \sigma_{tot}$. Considering the energy behaviour of $\sigma_{inel}/\sigma_{tot}$, the values of this ratio given by our model suggest a very slow increase to saturation, with $\sigma_{inel}/\sigma_{tot} = 0.77$ at Tevatron energies decreasing to 0.73 at 57 TeV.

The origin of such a slow approach to the black disc limit, turns out to be the same as with our previous set of parameters (see Ref. [15]): where one of the partial scattering amplitude, $A_{1,1} (s,b) < 1$ at all energies higher than $1.8 \text{TeV}$, while $A_{1,2} (s,b) \approx A_{2,2} (s,b) = 1$ for $b = 0$ at the same energies.

- We note that our new set of parameters with $\Delta \gamma_0 = 0.23$ does not change any qualitative features of the scattering amplitude. In particular, the impact parameter dependence in our model is similar to the $b$ dependence of our previous model [15]. Therefore, it is not surprising that we obtain good agreement with the experimental data for $d\sigma_{el}/dt$ as a function of $t$, at different energies (see Fig.3).

- The increase of $\Delta \gamma_0$ leads to stronger shadowing corrections, that manifest themselves in smaller values for the survival probabilities for the large rapidity gap ($S^2$), compared to what we previously obtained with $\Delta \gamma_0 = 0.21$ [15]. The $S^2$ calculated with our present parameters are:

$$S^2 = 7.02\% [9.76\%] \text{ at } W = 1.8 \text{TeV}; \quad S^2 = 2.98\% [6.3\%] \text{ at } W = 7 \text{TeV};$$

$$S^2 = 2.7\% [5.9\%] \text{ at } W = 8 \text{TeV}; \quad S^2 = 1.75\% [3.66\%] \text{ at } W = 14 \text{TeV};$$

(3.1)
[...] denotes the values obtained using our previous set of parameters (see Ref. [15]).

| $W = \sqrt{s}$ TeV | 1.8 | 7   | 8   | 14  | 57  |
|---------------------|-----|-----|-----|-----|-----|
| $\sigma_{tot}$ mb   | 79.2| 98.6| 101 | 109 | 130 |
| $\sigma_{el}$ mb    | 18.5| 24.6| 25.2| 27.9| 34.8|
| $\sigma_{sd}(M^2 < 0.05 s)$ mb | 8.2 + [2.07] | 10.7 + [4.18] | 10.9 + [4.3] | 11.5 + [5.81] | 13 + [8.68] |
| $\sigma_{dd}$ mb    | 5.12 + [0.38] | 6.2 + [1.24] | 6.32 + [1.29] | 6.78 + [1.59] | 7.95 + [5.19] |
| $B_{el}$ GeV$^{-2}$ | 17.4 | 20.2 | 20.4 | 21.6 | 24.6 |
| $\sigma_{inel}$ mb  | 60.7 | 74  | 75.6 | 81.1 | 95.2 |
| $\frac{d\sigma}{dt}|_{t=0}$ mb/GeV$^2$ | 326.34 | 506.4 | 530.7 | 608.11 | 879.2 |

**Table 1:** Predictions of our model for different energies $W$. The quantities appearing in square brackets [...] denote the contribution due to Pomeron interactions (so called non-GW part of the cross section).

### 4. Conclusions

Our goal in this paper is to deliver the message: we have succeeded in building a model for soft interactions at high energy, which provides a good description all high energy data, including the LHC measurements. This model is based on the Pomeron with a large intercept ($\Delta_F = 0.23$) and slope $\alpha_F' \approx 0$. We find no need to introduce two Pomerons: i.e. a soft and a hard one. The Pomeron in our model provides a natural matching with the hard Pomeron in processes that occur at short distances.

The attractive feature of our model is that we are able to describe data over the whole energy range. Our description of the data at lower energies is slightly worse than our description of the data at high energy $W \geq 900 GeV$. In addition we note that the qualitative features of the model are close to what we expect from $N=4$ SYM, which is the only theory that is able to treat the long distance physics on a solid theoretical basis.

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Figure 1: Comparison with the experimental data the energy behaviour of the total (Fig. 1-a), elastic (Fig. 1-b), single diffraction (Fig. 1-c), double diffraction (Fig. 1-d) and inelastic (Fig. 1-f) cross sections and elastic slope (Fig. 1-e). The solid lines show our present fit. The data has been taken from Ref. [20] for energies less than the LHC energy. At the LHC energy for total and elastic cross section we use TOTEM data [14] and for single and double diffraction cross sections are taken from Ref. [11].
Figure 2: $d\sigma_{el}/dt$ versus $|t|$ at Tevatron (blue curve and data) and LHC (black curve and data) energies ($W = 1.8\, TeV$, $8\, TeV$, $7\, TeV$ and $14\, TeV$ respectively). Data from Refs. [14, 23].