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Soft pomerons and the forward LHC data

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ABSTRACT

Recent data from LHC13 by the TOTEM Collaboration on σ_{tot} and ρ have indicated disagreement with all the Pomeron model predictions by the COMPETE Collaboration (2002). On the other hand, as recently demonstrated by Martynov and Nicolescu (MN), the new σ_{tot} datum and the unexpected decrease in the ρ value are well described by the maximal Odderon dominance at the highest energies. Here, we discuss the applicability of Pomeron dominance through fits to the *most complete set* of forward data from pp and $\bar{p}p$ scattering. We consider an analytic parameterization for $\sigma_{tot}(s)$ consisting of non-degenerated Regge trajectories for even and odd amplitudes (as in the MN analysis) and two Pomeron components associated with double and triple poles in the complex angular momentum plane. The ρ parameter is analytically determined by means of dispersion relations. We carry out fits to pp and $\bar{p}p$ data on σ_{tot} and ρ in the interval 5 GeV–13 TeV (as in the MN analysis). Two novel aspects of our analysis are: (1) the dataset comprises all the accelerator data below 7 TeV and we consider *three independent ensembles* by adding: either only the TOTEM data (as in the MN analysis), or only the ATLAS data, or both sets; (2) in the data reductions to each ensemble, uncertainty regions are evaluated through error propagation from the fit parameters, with 90% CL. We argument that, within the uncertainties, this analytic model corresponding to soft Pomeron dominance, does not seem to be excluded by the *complete* set of experimental data presently available.

1. Introduction

The forward elastic hadron scattering is characterized by two quantities, the total cross section and the ρ parameter, which can be expressed, at high energies, in terms of the amplitude $\mathcal{A}$ by [1]

$$\sigma_{\text{tot}}(s) = \frac{\text{Im}\,\mathcal{A}(s,t=0)}{s}, \quad (1)$$

$$\rho(s) = \frac{\text{Re}\,\mathcal{A}(s,t=0)}{\text{Im}\,\mathcal{A}(s,t=0)}, \quad (2)$$

where s and t are the energy and momentum transfer squared in the center of mass system, respectively.

In the Regge–Gribov formalism [2–4], the singularities in the complex angular momentum J-plane (t-channel) are associated with the asymptotic behavior of the elastic scattering amplitude in terms of the energy (s-channel). In the general case, associated with a pole of order N, the contribution to the imaginary part of the *forward* amplitude in the s-channel is $s^{\alpha_0}\ln^{N-1}(s)$, where α_0 is the intercept of the trajectory (see Appendix B in [5] for a recent short review). Therefore, for the total cross section we have

$$\sigma_{\text{tot}}(s) \propto s^{\alpha_0-1}\ln^{N-1} s,$$

and the following possibilities connecting the singularities at $J=\alpha_0$ and the asymptotic behavior: simple pole ($N=1$) $\Rightarrow$ $\sigma \propto s^{\alpha_0-1}$; double pole ($N=2$) at $\alpha_0=1$ $\Rightarrow$ $\sigma \propto \ln(s)$; triple pole ($N=3$) at $\alpha_0=1 \Rightarrow \sigma \propto \ln^2(s)$.

Most Pomeron models (even under crossing) consider leading contributions associated with either a simple pole at $J=\alpha_0$ (for example, Donnachie and Landshoff [6]) or a triple pole at $J=1$ (as selected by the COMPETE Collaboration [7,8] and used in successive editions of the Review of Particle Physics [9]).

Recently, new experimental information on σ_{tot} and ρ from LHC13 were presented by the TOTEM Collaboration [10,11]:

$$\sigma_{\text{tot}} = 110.6 \pm 3.4 \text{ mb},$$
$$\rho = 0.10 \pm 0.01 \text{ and } 0.09 \pm 0.01. \quad (3)$$

Remarkably, these two results seem not to be simultaneously described by conventional models based on Pomeron exchanges, as

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all those included in the detailed analysis by the COMPETE Collaboration in 2002 (see Figure 18 in [11]). On the other hand, the odd-under-crossing asymptotic contribution, introduced by Lukazsuk and Nicolescu [12] and named Odderon [13], provide quite good descriptions of the experimental data, as predicted by the Avila–Gauron–Nicolescu model [14] and demonstrated very recently in the forward analysis by Martynov and Nicolescu (MN) on pp and $\bar{p}p$ scattering in the interval 5 GeV–13 TeV [15].

However, in their data reductions, MN consider only the TOTEM data at the LHC energy region (excluding the ATLAS data at 7 and 8 TeV [16,17]) and although the resulting curves cross the central values of the data at 13 TeV, there is no reference to uncertainty regions in the theoretical results.

Now, given the tension between the TOTEM and ATLAS data at 7 TeV and mainly 8 TeV [18], the strict exclusion of the ATLAS data may not be a well justified procedure. Moreover, since the uncertainties in the TOTEM data are essentially systematic (and not statistical), the agreement between theoretical result and central value may have a limited significance (see Appendix A in [5]).

Also very recently, the data at 13 TeV have been analyzed in the context of a two-component eikonal model by Khoze, Martin and Ryskin [19], who also discuss inconsistencies relating maximal Odderon and the black disk limit [20].

In the present work, our purpose is to discuss the applicability of a Pomeron dominance at the highest energies, by taking into account: (1) all the experimental data presently available on σ_{tot} and ρ from pp and $\bar{p}p$ in the interval 5 GeV–13 TeV; (2) the uncertainties involved in the data reductions, interpolations and extrapolations.

To this end, we consider a parameterization for $\sigma_{tot}(s)$ consisting of two simple poles Reggeons, even and odd (a_2/f_2 and ρ/ω mesonic trajectories, respectively) and two Pomeron contributions, associated with double and triple poles in the J-plane, all the poles corresponding, respectively, to powers (RR), logarithmic (L1) and logarithmic-squared (L2) dependences for the total cross section. Inspired by the COMPETE notation we shall denote RRL1L2 model.

Following [18], we consider three ensembles of pp and $\bar{p}p$ data above 5 GeV, all of them comprising the same dataset in the region below 7 TeV, but distinguished by the addition of either the TOTEM data, or ATLAS data, or both sets.

The main question to be discussed here can be put as follows: Did the forward LHC data exclude the Soft Pomeron?

Based on the data reductions, the fit uncertainty region with 90% CL, the uncertainties in the σ_{tot} and ρ data at 13 TeV and further arguments, we are led to conclude that the RRL1L2 model is not excluded by the complete set of experimental data presently available on forward pp and $\bar{p}p$ scattering above 5 GeV.

This paper is organized as follows. After introducing the analytic model in Sect. 2, we present the fit procedures and results in Sect. 3, the discussions on all the results in Sect. 4 and our conclusions and final remarks in Sect. 5.

2. Analytic model – RRL1L2

The analytic parameterization for the total cross section is given by

$$\sigma_{tot}(s) = a_1 \left[\frac{s}{s_0}\right]^{-b_1} + \tau a_2 \left[\frac{s}{s_0}\right]^{-b_2} + A \ln\left(\frac{s}{s_0}\right) + B \ln^2\left(\frac{s}{s_0}\right), \quad (4)$$

where a_1, b_1, a_2, b_2, A and B are free fit parameters, $\tau = -1$ for pp, $\tau = +1$ for $\bar{p}p$ and s_0 is an energy scale. Here, as in the recent analyses by Fagundes, Menon and Silva [5,18], we assume this scale as fixed at the physical threshold for scattering states,

$$s_0 = 4m_p^2 \approx 3.521 \text{ GeV}^2, \quad (5)$$

with m_p the proton mass (see [21] for discussions on this choice).

From Eqs. (1)–(2), the analytic results for $\rho(s)$ have been obtained by means of even and odd singly subtracted dispersion relations (integral or derivative forms [22]):

$$\rho(s) = \frac{1}{\sigma_{\text{tot}}(s)} \left\{ -a_1 \tan\left(\frac{\pi b_1}{2}\right) \left[\frac{s}{s_0}\right]^{-b_1} + \tau a_2 \cot\left(\frac{\pi b_2}{2}\right) \left[\frac{s}{s_0}\right]^{-b_2} + \frac{\pi A}{2} + \pi B \ln\left(\frac{s}{s_0}\right) \right\}. \quad (6)$$

We note that these parameterizations, denoted RRL1L2, are analytically similar to the COMPETE model RRPL2, where P stands for a critical Pomeron (constant Pomeranchuck component) [7]. The differences concern: a) the phenomenological interpretation of the singularities (single or double poles), which may not be relevant; b) the presence of the free parameter A also in the $\rho(s)$ result; c) the energy scale s_0, which is a free fit parameter in the COMPETE analysis. We also recall that the logarithmic terms, L1 and L2, are present in the Block and Halzen parameterization (fixed energy scale) [23].

The RRL1L2 model has only 6 free fit parameters, a_1, b_1, a_2, b_2, A, and B, which are determined through fits to the experimental data on σ_{tot} and ρ data from pp and $\bar{p}p$ elastic scattering in the interval 5 GeV–13 TeV.

3. Fits and results

3.1. Ensembles and data reductions

The data below 7 TeV have been collected from the PDG database [9], without any kind of data selection or sieve procedure (we have used all the published data by the experimental collaborations). The data at 7 and 8 TeV by the TOTEM and ATLAS Collaborations can be found in Table 1 in [5], together with further information and complete list of references; the data at 13 TeV, Eq. (3), are also included.

Given the tension between the TOTEM and ATLAS measurements on σ_{tot} at 7 TeV and mainly 8 TeV, we shall consider three ensembles of pp and $\bar{p}p$ data above 5 GeV, both comprising the same dataset in the region below 7 TeV. We then construct:

Ensemble TOTEM (denoted T) by adding only the TOTEM data in the interval 7–13 TeV;

Ensemble ATLAS (A) by adding only ATLAS data at 7 and 8 TeV;

Ensemble TOTEM + ATLAS (T + A) by adding all the TOTEM and ATLAS data at 7, 8 and 13 TeV.

The data reductions were performed with the objects of the class TMinuit of ROOT Framework and using the default MINUIT error analysis [24]. We have carried out global fits using a χ^2 fitting procedure, where the value of χ^2_{min} is distributed as a χ^2 distribution with ν degrees of freedom. The global fits to σ_{tot} and ρ data were performed adopting an interval $\chi^2 - \chi^2_{min}$ corresponding, in the case of normal errors, to the projection of the χ^2 hyper-surface containing 90% of probability; this corresponds to $\chi^2 - \chi^2_{min} = 10.65$ (for 6 free parameters).

As a convergence criteria we consider only minimization result which imply positive-definite covariance matrices, since theoretically the covariance matrix for a physically motivated function must be positive-definite at the minimum. As tests of goodness-of-fit we shall consider the chi-square per degree of freedom, χ^2/ν, and the integrated probability, $P(\chi^2)$ [25].

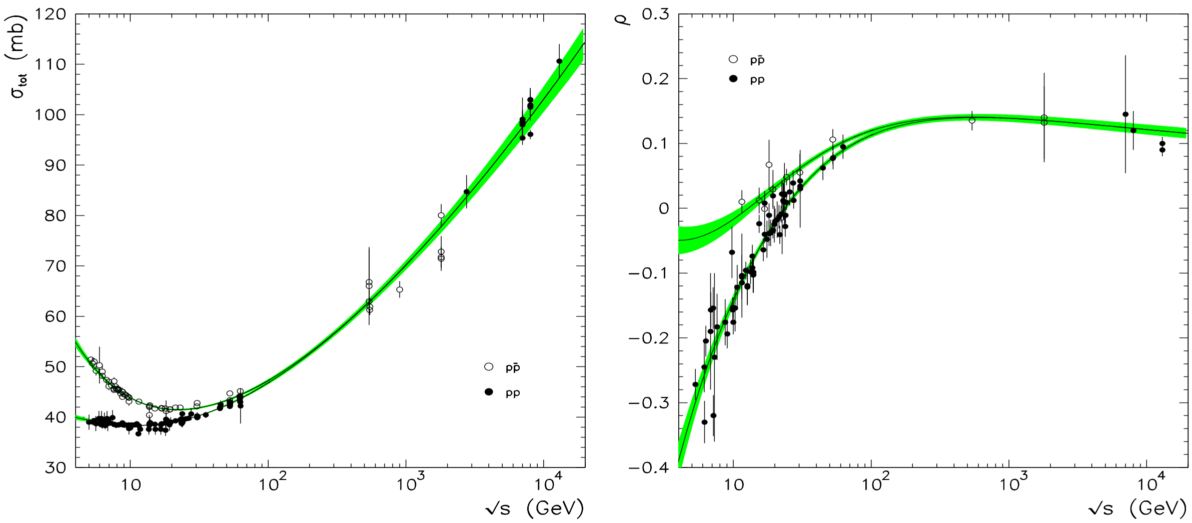

Fig. 1. Fit results with Model RRL1L2 (Table 1) to σ_{tot} and ρ data from ensemble T.

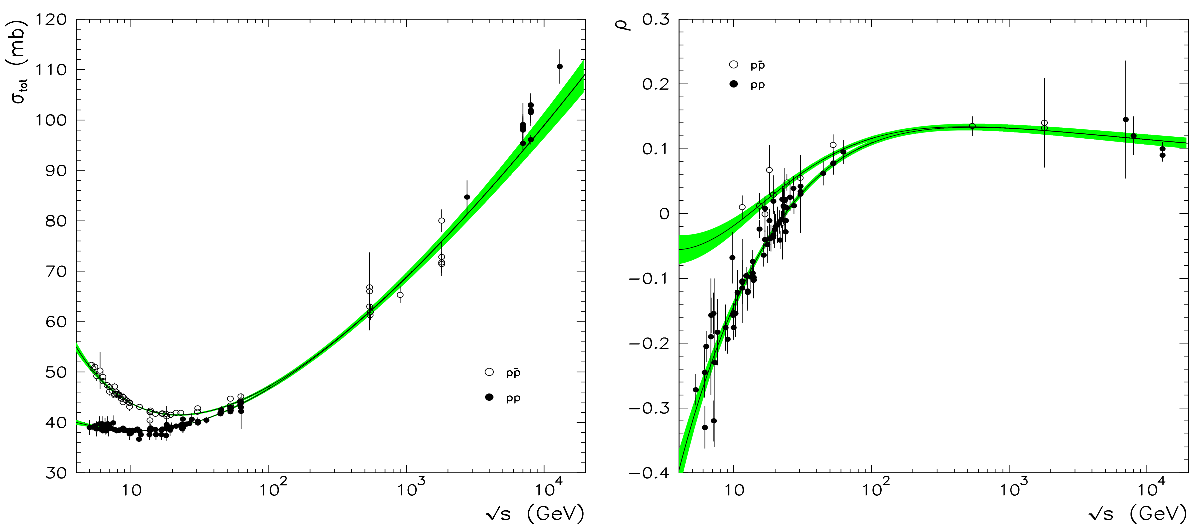

Fig. 2. Fit results with Model RRL1L2 (Table 1) to σ_{tot} and ρ data from ensemble A.

3.2. Fit results

The fit results are displayed in Table 1. Within CL of 90%, we have evaluated the uncertainty regions through error propagation from the fit parameters. The results with ensembles T, A and T + A are shown in Figs. 1, 2 and 3, respectively.

Table 1
Fit results with model RRL1L2, Eqs. (4)–(6).

Ensemble:	T	A	T+A
a_1 (mb)	58.6 ± 1.7	59.1 ± 1.7	58.8 ± 1.6
b_1	0.226 ± 0.018	0.238 ± 0.039	0.231 ± 0.017
a_2 (mb)	17.0 ± 2.3	17.1 ± 2.3	17.1 ± 2.3
b_2	0.547 ± 0.039	0.549 ± 0.040	0.548 ± 0.039
A (mb)	3.62 ± 0.37	3.97 ± 0.35	3.76 ± 0.33
B (mb)	0.135 ± 0.027	0.101 ± 0.026	0.122 ± 0.022
ν	249	236	251
χ^2/ν	1.210	1.136	1.238
$P(\chi^2)$	1.2×10^{-2}	7.4×10^{-2}	6.1×10^{-3}

4. Discussion

Before discussing the results, it is important to note that the three ensembles do not have the same character. On the one hand, T and A are a kind of “invented” ensembles, since they exclude one or another datasets from two different experiments. On the other hand, T + A encompasses all the experimental data presently available, namely all the information provided by the experimentalists from the LHC. For this reason let us discuss separately the results obtained with T and A, followed by those obtained with T + A.

Ensemble T and Ensemble A. It is well known that the TOTEM data indicate a rise of the total cross section faster than those indicated by the ATLAS Collaboration in the region 7–8 TeV [18]. This effect is clearly illustrated by the fit results in Figs. 1 and 2 with ensembles T and A, respectively: the σ_{tot} datum at 13 TeV is described within ensemble T, but not within ensemble A. In each case, the model predictions at 13 TeV read: $\sigma_{tot} = 107.3 \pm 2.7$ mb and $\rho = 0.1191 \pm 0.0078$ (ensemble T) and $\sigma_{tot} = 102.8 \pm 2.7$ mb and $\rho = 0.1121 \pm 0.0081$ (ensemble A).

Ensemble T + A. Taking into account all the experimental data presently available, the fit results with ensemble T + A is pre-

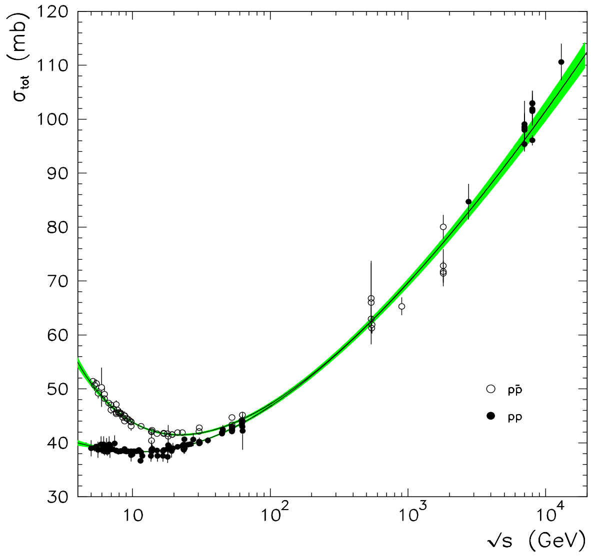

Fig. 3. Fit results with Model RRL1L2 (Table 1) to σ_{tot} and ρ data from ensemble T + A.

sented in Fig. 3. We note that at 13 TeV, the upper uncertainty region reaches the lower error bar of the σ_{tot} datum and the lower uncertainty region barely reaches the upper error bar of the of ρ data. In fact, at 13 TeV the model predictions read

$$\sigma_{tot} = 105.6 \pm 2.1 \text{ mb},$$
$$\rho = 0.1164 \pm 0.0061. \tag{7}$$

All the aforementioned predictions at 13 TeV with ensembles T, A and T+A are schematically displayed in Fig. 4, together with the TOTEM data.

Yet, in case of ensemble T+A, from Table 1, although the goodness of the fit is not good, $\chi^2/\nu = 1.238$, $P(\chi^2) = 6.1 \times 10^{-3}$ for $\nu = 251$, we notice that we did not use any kind of data selection and moreover the ensemble includes, for the first time, the ATLAS data at 7 and 8 TeV and the TOTEM data at 13 TeV.

Based on the above discussion, we understand that the fit result with ensemble T+A suggests that model RRL1L2 may not be excluded by the bulk of experimental data presently available. Further arguments in this direction are presented in what follows.

It is important to stress a central point in our analysis and on the strategy employed (see also Appendix A.2 in [5] for further discussions and complete list of reference to the experimental data to be quoted). In the recent paper by Martynov and Nicolescu, the authors did not include the ATLAS data at 7 and 8 TeV, because these points "are incompatible with the TOTEM data and their inclusion would obviously compromise the coherence of the overall data" [15]. The argument is based on the fact that ATLAS provided only one point at 7 TeV and one point at 8 TeV for the total cross section, which contrasts with the 4 points at 7 TeV and 5 points at 8 TeV by TOTEM, all consistent among them at each energy. The incompatibility can be exemplified by comparison of the ATLAS result at 8 TeV [17] and the latest TOTEM measurement at this energy [26], which differ by:

$$\frac{\sigma_{\text{TOTEM}} - \sigma_{\text{ATLAS}}}{\Delta\sigma_{\text{TOTEM}}} = \frac{103.0 - 96.07}{2.3} = 3. \tag{8}$$

Certainly, there may be some missing systematic effect involved, which is expected to be identified through further analyses.

However, it is important to recall that the situation is not so different from the inconsistencies characterizing the experimental

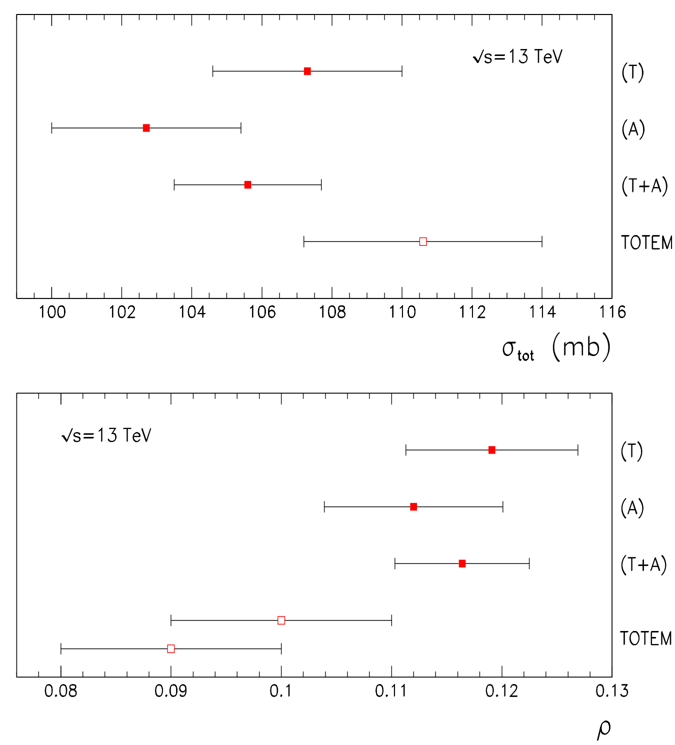

Fig. 4. Model predictions for σ_{tot} and ρ at 13 TeV from fits to ensembles T, A and T+A (filled squares), together with the TOTEM measurements (3) (empty squares).

information at the highest energy reached in $\bar{p}p$ scattering. Indeed, at 1.8 TeV, the differences between the CDF Collaboration and the E710 and E811 Collaborations can be estimated as 2.3 standard deviation:

$$\frac{\sigma_{\text{CDF}} - \sigma_{\text{E710}}}{\Delta\sigma_{\text{E710}}} = 2.3, \tag{9}$$

suggesting also some missing systematic uncertainty effect which, however, was never identified.

As a consequence, except for some particular studies excluding one or another set [27–29], most analyses consider the complete dataset with the three points at 1.8 TeV. As a further curious consequence, most analyses are not compatible with none of them, since the curves lie between the CDF datum (upper) and the E710/E811 data (lower). This is a characteristic behavior present in the majority of phenomenological approaches and also in the COMPETE, PDG, Martynov–Nicolescu analyses and obviously in our own work (Figs. 1, 2 and 3).

As already mentioned, in case of the LHC data, it is expected that the discrepancies might be resolved through further analyses and new data. However, we would like to call the attention to the possibility that the systematic differences between TOTEM and ATLAS could remain, even after further and detailed re-analyses. In this case, it would be difficult to carry out forward amplitude analyses (data reductions through analytic parameterizations for σ_{tot} and ρ), without taking account of the bulk of experimental information available from the LHC, namely all the TOTEM and ATLAS results.

Within this possible scenario, the analysis and results here presented may have an important role for future investigation, since they suggest that the Pomeron dominance may be not excluded by the experimental data presently available. In fact, by comparing the predictions of the RRL1L2 model within ensemble T+A at 13 TeV, (7), with the TOTEM measurements, (3), we obtain:

$$\frac{\sigma_{\text{TOTEM}} - \sigma_{\text{predic}}}{\Delta\sigma_{\text{TOTEM}}} = \frac{110.6 - 105.6}{3.4} = 1.47,$$

$$\frac{\rho_{\text{predic}} - \rho_{\text{TOTEM}}}{\Delta\rho_{\text{TOTEM}}} = \frac{0.1164 - 0.095}{0.010} = 2.14.$$

Therefore, the differences are smaller than those associated with the TOTEM–ATLAS at 8 TeV, (8), and with the CDF–E710/E811 difference at 1.8 TeV, (9). We understand that, in the experimental context presently available, these facts corroborate the effectiveness of the model, the importance of the ensembles and the adequacy of the data reduction.

5. Conclusions and final remarks

We have presented a forward amplitude analysis on the experimental data from pp and $\bar{p}p$ scattering in the energy region from 5 GeV up to 13 TeV. We have used analytic parameterizations for $\sigma_{tot}(s)$ and $\rho(s)$ characterized by Pomeron dominance at the highest energies, represented by double and triple poles. Up to our knowledge, this is the first quantitative analysis including in the data reductions all the experimental data presently available.

Based on the fit results and taking into account both, theoretical and experimental uncertainties, we have argued that the RRL1L2 model may not be excluded by the bulk of experimental data.

We notice that this RRL1L2 parameterization, may not be the best representative approach for a Pomeron model in forward scattering. The main point was to show that even a simple parameterization, with only 6 free fit parameter and even (under crossing) leading contributions, may not be excluded in fits to a dataset including all the experimental information that have been obtained at the LHC on σ_{tot} and ρ.

We are presently investigating different forward Pomeron models,[1] now taking into account: (1) confidence levels with one and two standard deviations (68.6% and 95.5%, respectively); (2) the introduction of one more free parameter, represented by the subtraction constant in singly subtracted dispersion relations. The analysis is in progress and the results shall be reported elsewhere [31].

Certainly, to understand and/or to resolve the tension between the TOTEM and ATLAS data is a crucial point for amplitude analyses and unquestionable conclusions. In this direction, beyond further re-analysis, measurements on both σ_{tot} and ρ at 13 TeV by the ATLAS Collaboration, may bring new insights on the subject. In conclusion, at this stage, it may still be premature to exclude one or another set of data from different experiments.

[1] Some preliminary results have already been presented in [30].

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