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The structure and analytic properties of the scattering amplitude at LHC energies

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Elastic proton-proton scattering is reviewed starting from the results of the LHC experiments conducted by the TOTEM and ATLAS collaborations, and the HEGS model and a simple phenomenological parametrisation are compared with the new data on the differential elastic proton-proton scattering cross section, which detect a non-exponential behaviour of the differential cross sections in the first diffraction cone. We consider the influence of various assumptions on the extraction of the elastic scattering parameters, and on the deduction of the total cross section.

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Diffractive processes play an important role for our understanding of hadronic reactions at high energies. They result from the exchange of a colour-singlet object called the Pomeron that is the dominant contribution at the LHC, and which makes all diffractive processes grow with energy. The simplest way to describe it is to use a simple pole at $j = 1 + \epsilon$ [1], and unitarise it via an eikonal scheme. Elastic hadron scattering is the simplest diffractive reaction and it allows to investigate the basic properties of the diffractive processes [2]. The new data from the TOTEM [3] and ATLAS [4] collaborations give very important information about this reaction.

Unfortunately, the measurements of the elastic differential cross sections at small momentum transfer and the subsequent derivation of the total cross sections $\sigma_{tot}(s)$ and of the values of $\rho(s, t = 0)$ − the ratio of the real part to the imaginary part of the scattering amplitude − do not agree. The difference between the TOTEM and ATLAS results for the total cross section is 3 mb at 7 TeV and increases to 6 mb at 8 TeV. This is reminiscent of the conflicting Tevatron data for the total cross section at $\sqrt{s} = 1.8$ TeV.

We shall explain here that the TOTEM data at 7 TeV for the differential cross sections seem to be somewhat inconsistent with their determination of $\sigma_{tot}(s)$ and $\rho(s, t = 0)$ [5]. To compare the data of the two collaborations, we need a model. We choose the High Energy Generelazed Structure model (HEGS), which satisfies the basic analytical properties of the S matrix [6], and describes quantitatively most existing experimental data in wide energy and momentum-transfer regions, including the Coulomb-hadron interference region.

The model describes very well the data at $\sqrt{s} = 7$ TeV [7] and 8 TeV [8] and gave predictions for $\sqrt{s} = 13$ TeV [9]. It has only a few free parameters and it embodies the main analytic requirements. The real part of the amplitude can be obtained from crossing symmetry and the energy dependence comes from a single (unitarized) pomeron. When we compare the model with experimental data on the differential cross sections taking into account only statistical errors we find that the ATLAS data is well described. However, the TOTEM data are described only if one multiplies the results by normalization coefficients that depend on the dataset used, $n_{7TeV} = 0.97$ and $n_{8TeV} = 0.91$, with other parameters parameters compatible with those from the fit to ATLAS data. Hence, independently from the validity of the model, we find that the data from the TOTEM Collaboration lie slightly above those from ATLAS. It is likely that this is the cause of the difference between the values of the total cross section.

We can also study the data on the differential cross sections though a simple phenomenological parametrisation that includes an exponential form factor with a non-linear argument in t, and the possibility of additional normalization coefficients. The possibility of a non-exponential behaviour of the differential cross sections at small t has a long history. One of the attempts to reproduce such a non-linear behaviour used the contribution of the 2-meson loop, which adds a term $\sqrt{(4m_\pi)^2 - t} - 2m_\pi$ to

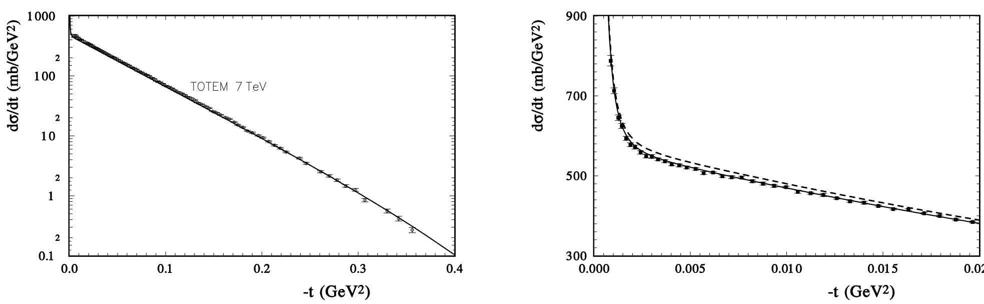

Figure 1: Comparison of the differential cross sections obtained in the HEGS model with experimental data (the right-hand figure is for $\sqrt{s} = 7$ TeV and the left-hand one for $\sqrt{s} = 13$ TeV and $\sqrt{s} = 14$ TeV and for the preliminary data at 13 TeV [11].

the pomeron slope, with m_π the pion mass. At small $|t|$ such a term differs only very little from the standard slope $\alpha' = B_1 t/2$. and one can use the approximation

$$\sqrt{(4m_\pi)^2 - t} - 2m_\pi \approx -\frac{t}{512 m_\pi}\left[128 + 8\frac{t}{m_\pi^2}\right].$$

The difference becomes significant only at $-t \geq 0.3$ GeV^2. This is the region that the original work tried to describe [10]. For this term to matter at small $|t|$ one would need to reduce m_π.

Hence we take the scattering amplitude in the simple form

$$\mathcal{A}(s,t) = \frac{ihs}{4\pi}\log^2\left(\frac{s}{s_0}\right)\left(\frac{s}{s_0}\right)^{\frac{B_1}{2}t + \frac{B_2}{2}t^2} F_1^2(t)$$

where the non-linear behaviour is described by the additional term $B_2 t^2/2$, $s_0 = 1$ GeV^2 and $F_1(t)$ is the elastic form factor. We consider the three data sets of TOTEM and the two sets of ATLAS. We first simultaneously analyse the data of both collaborations with only statistical errors and fix the additional normalization coefficient to $n_i = 1$. In this case the χ^2 is very large, as shown in the first column of Table 1.

We then fit using systematic and statistic errors added in quadrature. In this case the χ^2 substantially decreases, as seen in the second column of Table 1. If we then include the normalization coefficients in our fitting procedure as free parameters and consider again only statistical errors, we obtain a reasonable χ^2, but the normalization coefficients are significantly different between TOTEM and ATLAS data. As in the HEGS model we see again that the data of the ATLAS collaborations are lower those of the TOTEM collaboration. Most remarkably, the obtained values for the total

Table 1: The results of the analysis of the experimental data on the differential cross sections, obtained by the TOTEM and ATLAS collaborations at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV taking into account the additional normalization of the differential cross section n_i (the first column shows the results for statistical errors only, the second for the statistical and systematic errors added in quadrature, the third for statistical errors only, but with an extra normalisation factor for each dataset).

	statistical	statistical+ systematic	statistical+ normalisation
χ^2	48337	421	1812
h (GeV^{-2})	0.30	0.30	0.31
B_1 (GeV^{-2})	0.55	0.55	0.58
B_2 (GeV^{-4})	-0.39	-0.39	-0.26
$\sigma_{tot}(7\ TeV)$ (mb)	95.3	95.1	96.8
$\sigma_{tot}(8\ TeV)$ (mb)	98.2	98.0	99.7
TOTEM n_i at 7 TeV			0.97
TOTEM n_i at 8 TeV			0.95,0.94
ATLAS n_i at 7 TeV			1.02
ATLAS n_i at 8 TeV			1.06

cross sections do not change much for all the considered variants. In all cases the value of $\sigma_{tot}(s)$ is close to that obtained by the ATLAS Collaboration.

In conclusion, the new LHC data crucially constrain the models of soft hadronic interactions. We find that elastic scattering may reflect the generalized structure of the hadron, from GPDs which open a new way to connect elastic and inelastic interactions. Also, the standard eikonal approximation works well from $\sqrt{s} = 9$ GeV to 8 TeV.

Our calculations, based on the simplest phenomenological form of the scattering amplitude, confirm the conclusions from the HEGS model that there is a difference in the normalization of the differential cross sections in TOTEM and ATLAS data. The new data show that the hadron interactions at large distances, which reflects the properties of the differential elastic cross sections at small momentum transfer, can have complicated properties. This means that we need to examine carefully the fine structure of the diffraction peak to understand the effects of a non-exponential behaviour and maybe detect oscillations as the momentum transfer changes. This is tightly connected with the study of possible contributions from the hard Pomeron and the Odderon. All these questions may have an effect on the determination of the total cross section and on the extraction of the ratio of the real part to the imaginary part of the scattering amplitude. New experimental data at 13 and 14 TeV, measured with high accuracy, will shed new light on these issues.

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