New features in the differential cross sections measured at the LHC

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The critical analysis of the new experimental data obtained by the ATLAS Collaboration group at 13 TeV is presented and the problem of the tension between data of the ATLAS and TOTEM Collaboration is considered. The analysis of new effects discovered on the basis of experimental data at 13 TeV \[1,2\] and associated with the specific properties of the hadron potential at large distances is carried out taking account of all sets of experimental data on elastic pp-scattering obtained by the TOTEM and ATLAS Collaborations in a wide momentum transfer region. It also gives quantitative descriptions of all examined experimental data with a minimum of fitting parameters. It is shown that the new features determined at a high statistical level give an important contribution to the differential cross sections and allow the research into hadron interactions at large distances.

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I. INTRODUCTION

To get hard predictions for hadronic interactions at ultrahigh energies, we need to know with the highest possible accuracy the structure of hadrons and their interactions. The main purpose of a new accelerator is to find new effects in particle interactions. This especially concerns studies of elastic hadron scattering at the LHC. It gives information about hadron interaction at large distances where perturbative QCD does not work and a new theory such as instanton or string theory, has to be developed.

The first measurements of the TOTEM Collaboration confirmed the non-linear behavior of the slope of the differential cross sections at a small momentum transfer \[3\], which shows a complicated picture of the hadron interaction at super high energies. The unique experiments of the TOTEM-SMS and ALFA-ATLAS Collaborations at 13 TeV gave experimental data with unprecedentedly small scattering angles and narrow \(\Delta t\) at small momentum transfer \[4,5\]. However, it is necessary to note some problems with the normalization of experimental data.

The study of the experimental data at 13 TeV obtained by the TOTEM Collaboration reveals new effects in the behavior of differential cross sections, oscillations \[1\], which are practically independent of the normalization of differential cross sections (see below), as well as an additional anomalous term in the scattering amplitude with a large slope \[2\], which gives necessary contributions at small momentum transfer. It is important to study the full sets of experimental data obtained at LHC \(7 \leq \sqrt{s} \leq 13\) TeV by both Collaborations. For this purpose, the high energy generalized structure (HEGS) model was chosen as it has a minimum fitting parameters and gives a quantitative description of the differential cross section in a huge energy region \(9 \leq \sqrt{s} \leq 13000\) GeV and simultaneously in the Coulomb-hadron interference region and a large momentum transfer \[6–8\].

In the second section of the paper, a short analysis of experimental data on the differential cross sections of elastic proton-proton scattering is presented. In the third section, the new effects are analyzed in the framework of the HEGS model taking into account experimental data of all sets of the TOTEM and ATLAS Collaborations obtained at \(2.7 - 13\) TeV. In the fourth sections, the results and some consequences are discussed. The conclusions are given in the final section.

II. EXPERIMENTAL DATA

Now there are 9 independent sets of elastic \(pp\) differential cross sections obtained by the ATLAS and TOTEM Collaborations at LHC energies \(\sqrt{s} = 7 - 13\) TeV, 6 of them are measured at a small momentum transfer \(t\) including the Coulomb-hadron interference region (2 obtained by ATLAS and 3 by the TOTEM Collaboration). The other 3 sets are measured at large \(t\) including the region of the dip-bump structure. At small \(t\) the values of \(\sigma_{\text{tot}}(s)\) and \(\rho(s, t = 0)\) were obtained on the basis of experimental data. Some tension between \(\sigma_{\text{tot}}(s)\) obtained by the ATLAS and TOTEM Collaborations should be noted. The difference is 3.15 mb at 7 TeV and grows to 5.6 mb at 8 TeV. Note that in \[6\] some contradictions between the obtained \(\sigma_{\text{tot}}(s)\) and \(\rho(s, t = 0)\) by the TOTEM at 7 TeV were shown. In the paper \[11\], some discrepancy between the slopes of the differential cross sections measured by the TOTEM at 7 and 8 TeV were noted.

Until recently, we had no ATLAS-ALFA data at 13 TeV. Now these data are published \[5\]. The tension between values of \(\sigma_{\text{tot}}(s)\) increases up to 5.75 mb. In a recent paper \[12\], the importance of the contribution of inelastic scattering at small angles, especially in the case of determining the total cross section by the luminosity independent
TABLE I. Sets of $d\sigma/dt$ and $\chi^2_{dof}$ obtained in the HEGS model ($k_i$ - additional normalization coefficient)

| $\sqrt{s}$ (TeV) | n | $-t_{min}$ (GeV$^2$) | $-t_{max}$ (GeV$^2$) | $\sum \chi^2_{dof}$ | $k_{norm}$ |
|------------------|---|---------------------|---------------------|------------------|-----------|
| 7 T(1)           | 79 | 0.0699              | 162.1               | 2.19             | 1.12      |
| 7 A(1)           | 70 | 0.0559              | 86.5                | 1.29             | 1.15      |
| 8 T(2)           | 65 | 0.0488              | 66.3                | 1.07             | 1.16      |
| 8 A(2)           | 60 | 0.0422              | 55.3                | 0.97             | 1.16      |
| 8 T(3)           | 55 | 0.0361              | 49.7                | 0.96             | 1.16      |
| 8 T(4)           | 50 | 0.0305              | 47.8                | 1.02             | 1.01      |
| 13 T(5)          | 40 | 0.0207              | 34.2                | 0.92             | 1.11      |
| $\sum AT$        | 712| 0.0007              | 2.4                 | $\chi_{exp}$    | 715       |

method. We can remember the large difference in the measurements of $\sigma_{tot}(s)$ by the luminosity independent method (72 and 80 mb) by two Collaborations at the Tevatron. However, in our opinion the situation is more complicated and requires careful analysis of the new data.

The new experiment of the ATLAS-ALFA Collaboration [5] presented unique results. The position of Roman Pot situated at very large distances (2400 m) allows one to obtain new data at very small angles with small $\Delta t$. The experiment for first time gave five new experimental points in the essential Coulomb-nuclear interference region. The first experimental point begins from $-t = 0.00025 \text{ GeV}^2$ with $\Delta t = 0.0001 \text{ GeV}^2$. To our regret, this first point has a large error (only statistical error reaching 26 per cent). However, there are at least six-seven more points in the Coulomb Nuclear Interference (CNI) region. Three-four of them overlap the region where the TOTEM Collaboration gave own experimental points. Obviously, we can see that the ATLAS points lie systematically below the TOTEM points. Hence, they require some additional normalization. This is so, and our model description of both the sets shows, in all variants of the model, the difference in the normalization is about 11% - 13%. As the points lie in the significant CNI region, we can check up these experimental points of ATLAS by comparing their momentum transfer dependence with the $t$ dependence of the contribution of the Coulomb amplitude.

Let us extract from the differential cross section of elastic scattering the term of Coulomb-nuclear interference, which is determined by the contribution of the pure Coulomb amplitude and the contribution of the pure hadron amplitude

$$\frac{d\sigma}{dt}_{\text{CNI}} = \frac{d\sigma}{dt}_{\text{exper.}} - \frac{d\sigma}{dt}_{F^2_C} - \frac{d\sigma}{dt}_{F^2_h}$$

(1)

The first term proportional to the square of the Coulomb amplitude is calculated exactly and has the $1/t^2$ dependence. The second term proportional to the square of the hadron amplitude has small $t$ dependence in the examined $t$ region. The result proportional to the product of Coulomb and hadron amplitude has the $1/t$ dependence. For comparison with the TOTEM data, let us take our model description of all sets at $7 - 13 \text{ TeV}$ without recent ATLAS data (see below) and calculate the differential cross sections at the same points of momentum transfer as the ATLAS experimental data at 13 TeV. For comparison of the $t$ dependence, let us take an artificial term that has a simple $1/t$ dependence $F_{Ch}(t) = 8\alpha_{em}/t$, where $\alpha_{em}$ is a fine electromagnetic structure constant. The results are presented in Table 2. Obviously, the value of $\Delta CNI$ (third column of Table 1) obtained from the ATLAS data has no normal $1/t$ dependence and differs considerably from the results obtained from TOTEM artificial data (TABLE 2, last column). In Fig. 1, the data are compared with the CNI term with hadron amplitudes, used by ATLAS (short dashed line), and with HEGS model calculations (long-dashed line), as well as with the term which represents the true $1/t$ dependence $F_{Ch}(t) = 8\alpha_{em}/t$. We can see that the model calculations exactly reproduce the $1/t$ dependence.
TABLE II. $\Delta CNI = d\sigma/dt_{CNI}$ mb/GeV$^2$

| $-t$ (GeV$^2$) | $d\sigma/dt_{ATLAS}$ | $-\Delta CNI$ | $d\sigma/dt_{mod}$ | $-\Delta CNI$ |
|---------------|----------------------|--------------|-------------------|--------------|
| 0.00029       | 3662                 | -33          | 3291              | 417          |
| 0.0004        | 2136                 | 33           | 1952              | 296          |
| 0.00051       | 1401                 | 146          | 1396              | 229          |
| 0.00067       | 998                  | 130          | 1034              | 166          |
| 0.00086       | 797                  | 104          | 846               | 130          |
| 0.00112       | 680.1                | 75           | 731.1             | 98           |
| 0.00143       | 610.6                | 62           | 620.7             | 75           |

Fig. 1. $\Delta CNI(t)$ extracted from experimental data: open squares and full squares - with different magnitudes of $\sigma_{tot}(s) = 104$ mb and $\sigma_{tot}(s) = 110$ mb with ATLAS form of $F_h(t)$; circles - extracted from the model representation of TOTEM data; hard line - representation of the CNI-term in the form $F_{Ch}(t) = 8\alpha_{em}/t$; long dashed line - HEGS model calculations of the CNI term; short dashed line - model calculations with ATLAS phenomenological fit of $F_h(t)$.

The points calculated with the hadron amplitude with $\sigma_{tot} = 104$ mb are much lower and give the $1/t$ dependence only for $-t > 0.0005$ GeV$^2$. The points obtained by using $\sigma_{tot} = 110$ mb do not give the $1/t$ dependence for all points. It means that simple additional normalization does not improve the situation.

In Fig. 2, the comparison of the TOTEM and ATLAS data at 13 TeV are presented. Obviously, the data of ATLAS above $-t = 0.0005$ GeV$^2$ are systematically lower than the TOTEM data. It means that additional corrections of the normalization of experimental data is required. This explains the tension between the values of $\sigma_{tot}(s)$ presented by the Collaborations. In our model fitting, we take into account only statistical errors whereas systematical errors are taken into account as additional correction coefficients of the normalization.

III. MODEL DESCRIPTION OF ALL EXPERIMENTAL SETS AT 7 - 13 TEV

There are many different semi-phenomenological models which give a qualitative description of the behavior of differential cross sections of elastic proton-proton scattering at $\sqrt{s} = 13$ TeV (for example [14, 15]). Some examples can be found in the review [8]; hence, we do not give a deep analysis of those models. Our model was compared with other in [7] (for example, see Table VII). One of the common properties of practically all models is that they take into account statistic and systematic errors in quadrature forms and in most part give only a qualitative description of the behavior of the differential cross section in a wide momentum transfer region. The analysis of systematic errors,
FIG. 2. Comparison of experimental data on the differential cross sections at small momentum transfer of the TOTEM and ATLAS Collaboration only with statistical errors. (Full circles - ATLAS data, crosses - TOTEM data.)

for example, of the TOTEM collaboration, shows that the main uncertainty is determined by Luminosity. This affect experimental data of one set in one direction. Additional normalization reflect such a situation. This method is used by many other research groups, which deal with many different sets of experimental data, for example, in analysis of different parton distribution functions (PDF). In this paper, we use the high energy generalized structure (HEGS) model that is based on generalized parton distributions. The generalized parton distributions (GPDs) represent the basic properties of the hadron structure. Different properties of the hadron structure are reflected in the elastic scattering amplitude. Our form of the momentum transfer dependence of GPDs allows us to calculate the electromagnetic form factors, gravitomagnetic form factors, transition form factors, and Compton form factors. As a result, the description of various reactions is based on the same representation of the hadron structure. This allows us to use both hadron form factors (electromagnetic and gravitomagnetic) to build a high energy generalized structure model of elastic nucleon-nucleon scattering. The value and the energy and momentum transfer dependence of the real part of the elastic scattering amplitude are determined by the complex energy \( \hat{s} = s \exp(-i\pi/2) \). Hence, the model does not introduce some special functions or assumptions for the real part of the scattering amplitude. The final elastic hadron scattering amplitude is obtained after unitarization of the Born term. So, first, we have to calculate the eikonal phase in the most favorable eikonal unitarization scheme. The eikonal phase corresponds to the Born term of the scattering amplitude, and in the common case corresponds to the spin-dependent potential.

In our paper [1], it was shown that the new data of the TOTEM Collaboration at 13 TeV show the existence in the scattering amplitude of the oscillation term, which can be determined by the hadron potential at large distances. In the analysis of experimental data of both the sets of the TOTEM data additional normalization was used. Its values reach sufficiently large magnitudes. In this case, a very small \( \chi^2_{\text{dof}} \) was obtained with taking into account only statistical errors and with a few number of free parameters in the scattering amplitude, which was obtained in our High Energy Generalized Structure (HEGS) model [6, 7]. However, an additional normalization coefficient reaches a sufficiently large value, about 13%. It can be in a large momentum transfer region, but is very unusual for a small momentum transfer. However, both sets of experimental data (small and large region of \( t \) overlap in some region and, hence, affect each other’s normalization. It is to be noted that the value of the normalization coefficient does not impact the magnitudes and properties of the oscillation term. We have examined many different variants of our model (including large and unity normalization coefficient), but the parameters of the oscillation term have small variations.

In the present work, all sets of the TOTEM and ATLAS data at 7 − 13 TeV (at first, not including recent ATLAS data at 13 TeV) are analyzed with additional normalization equal to unity and taking into account only statistical errors in experimental data.
To study the new effects in elastic scattering as a basis, we take our high energy generalized structure (HEGS) model[3, 4] which quantitatively describes, with only a few parameters, the differential cross section of $pp$ and $pp$ from $\sqrt{s} = 9$ GeV up to 13 TeV, includes the Coulomb-hadron interference region and the high-|t| region up to |t| = 15 GeV$^2$ and quantitatively well describes the energy dependence of the form of the diffraction minimum[8]. To determine the new effects, the model is simplified as much as possible. To avoid possible problems connected with the low-energy region, we consider here only the asymptotic variant of the model, leaving only the hadron spin-flip amplitude, which has no energy dependence, and taking it in a simple exponential form with two parameters. As was made in all variants of the model, we take into account in the slope the $\pi$ meson loop in the t-channel, as was proposed in[16, 17] and recently studied in[18]. The total elastic amplitude in general gets five helicity contributions, but at high energy, it is sufficiently to keep only spin-non-flip hadron amplitudes. In this case, one take $F(s, t) = F_h(s, t) + F_{em}(s, t)e^{i\varphi(s, t)}$ where $F_h(s, t)$ comes from the strong interactions, $F_{em}(s, t)$ from the electromagnetic interactions and $\varphi(s, t)$ is the interference phase factor between the electromagnetic and strong interactions[19]. Note that all five spiral electromagnetic amplitudes are taken into account in the calculation of the differential cross sections. It is essential that in the model only the Born term is taken in an analytic form. After that, the eikonal phase is calculated by the Fourier-Bessel method. Then using the standard eikonal representation, the full scattering amplitude is calculated numerically. The Born term of the elastic hadron amplitude at large energy can be written as a sum of two pomeron (related with two and three (cross even) gluons) and odderon contributions (cross odd - three gluon amplitude). Note that both pomeron contributions have the same positive sign, this is an essential difference from other models.

$$F(s, t)_B = s^{\alpha_0} \left( C_F F_1^2(t) \hat{s}^{\alpha'} - t + (C_F \mp i C_G t) A^2(t) \hat{s}^{\alpha_4} \right),$$ (2)

$$\text{(3)}$$

As seen, all terms have the same intercept $\alpha_0 = 1 + \epsilon_0 = 1.11$, and the pomeron slope is fixed at $\alpha' = 0.24$ GeV$^{-2}$. With taking into account the effects of a two-$\pi$ meson loop, we have $\alpha' = \alpha_0(1 + x^2_\pi e^{b_1|t|Lm(s)})$ with $x_\pi = \sqrt{4m_\pi - t}$.

The model takes into account the electromagnetic $F_1(t)$ and gravitomagnetic $A(t)$ form factors, which correspond to the charge and matter distributions[20]. Both form factors are calculated as the first and second moments of the same Generalized Parton Distribution (GPDs) function. The Born scattering amplitude has three free parameters (the constants $C_i$) at high energy: two for the two pomeron amplitudes and one for the odderon. The real part of the hadronic elastic scattering amplitude is determined through the complexification $\hat{s} = -is$ to satisfy the dispersion relations. The oscillatory function was determined[11] $f_{osc}(t) = h_{osc}(1 + i)J_1(\tau)/\tau; \ \tau = \pi (-t)/t_0 G_{em}^2(t)$, (4)

here $J_1(\tau)$ is the Bessel function of the first order and $G_{em}(t) -$ the electromagnetic form factor of the proton. This form has only two additional fitting parameters and allows one to represent a wide range of possible oscillation functions.

As was found in[2], the behavior of experimental data requires an additional term to scattering amplitude in the CNI region, which is determined by the hadron interaction at large distances. In the present work, it takes a simple exponential form

$$F_d(t) = h_d(i - \rho(t))e^{-(B_1|t|+B_2|t|^2)\log s}\hat{s}^{\alpha_3} G_{em}^2(t),$$ (5)

where $\rho(t)$ is determined by the main amplitude $F(s, t)$. Taking into account all sets of experimental data (Table 1), 715 experimental points were used in the fitting procedure with thirteen free parameters. After the fitting procedure, we obtain $\chi^2/n.d.f. = 1.06$ (remember that we used only statistical errors) with additional normalization coefficients

$$n_A1 = 0.97, n_{T1} = 1.02, n_{T2} = 0.96, n_A2 = 0.96, n_{T3} = 1.07,$$

$$n_{T4} = 0.96, n_{T5} = 1.09, n_{T6} = 0.99, n_{A3} = 0.96$$

If we add the experimental data of the TOTEM Collaboration at $\sqrt{s} = 2.76$ TeV, the number of experimental points increases to 778 and we obtain $\chi^2_{data} = 1.07$.

The constants of the oscillatory and anomalous terms are determined with high accuracy $h_{osc} = 0.36 \pm 0.013; \ h_d = 1.41 \pm 0.07 GeV^{-2}$. They can be compared with the same constants obtained from the analysis of the TOTEM data at 13 TeV[1, 2] $h_{osc} = 0.16 \pm 0.02; \ h_d = 1.7 \pm 0.01 GeV^{-2}$. 
FIG. 3. a) (left side) The effect of the oscillation term in the even and odd parts of the intervals of momentum transfer of ATLAS data at 13 TeV (hard and dotted lines) The same but with shifted intervals by half the period - (short dashed lines); b) (right side) $R \Delta_{th}$ of eq.(6) (the hard line) and $R \Delta_{ex.}$ eq.(7) (the tiny line) of ATLAS data at 13 TeV.

FIG. 4. The differential cross sections are calculated in the framework of the HEGS model at $2 - 13$ TeV (the experimental points with only statistical errors). a) [right] the full region of $t$; b) [left] the magnification of the region of the small momentum transfer; (the data of ATLAS ($\sqrt{s} = 13$ TeV) are drawn without an additional coefficient of the normalization.

It can be seen that additional experimental information leads to an increase in the magnitudes of the oscillation term. If such peculiarities are related with the specific properties of the TOTEM 13 TeV data only, the constants have to decrease and errors increase essentially. Note that the form and value of the oscillation are independent of additional normalization of the set of experimental data. The normalization shifts all data of one set in one direction. The oscillation term lead to increasing or decreasing some parts of the model calculate differential cross sections. Hence, it is reflecting the deviations from the average position of experimental data of the set.

Now let us add the new data of the ATLAS Collaboration at 13 TeV into our consideration. As there are some problems with the points in the CNI region, let us take them with some increasing errors (for example, twice as large or proportional to the error of the first point). The number of experimental points is 795 and $\chi^2 = 903$ is obtained. In this case, additional normalization for the ATLAS data is $n_{A3} = 1.06$, and the normalization of the TOTEM data at 13 TeV is $n_{T6} = 0.94$. This reflects the tension between these data. But the magnitudes of the corresponding constants of the new terms practically do not change. This means that such additional information does not change the determination of these peculiarities. Taking into account the experimental data of the TOTEM Collaboration at
2.9 TeV leads to the same result. In this case, the number of experimental points increases to 858 and $\chi^2 = 984$ is obtained. But again, the magnitudes of the constants practically do not change.

The contributions of the oscillatory term in the differential cross section of the ATLAS data at 13 TeV are presented in Fig.3 (a,b). In Fig.3a, the results of the statistical method of the two chosen independent selections are shown. This is the result of the procedure in which the whole examined region of momentum transfer is divided into some equal intervals, and then deviations of experimental data from some smooth curve in units of errors of experimental data were summed separately in the odd and even intervals. If the some periodic structure is present in experimental data, it gives increasing sums of the contribution in the odd and even intervals in the case of coincidence of the period with the span of the interval. If the beginning of intervals is shifted by half the period, the sums will be near each other.

The results of the description of the differential cross sections are represented in Fig.4(a,b). We can see that the diffraction minimum has a sharp form at 7 and 13 TeV, but a less pronounced at $\sqrt{s} = 2.79$ TeV.

In Fig.5, the $s$ and $t$ dependence of the imaginary (left) and real (right) parts of the elastic scattering amplitude obtained in the model with taking into account additional effects are represented. Note that the real part of the scattering amplitude has the first zero at small momentum transfer which changes with energy. The imaginary part of the scattering amplitude has the first zero at the essentially large momentum transfer. It determines the position of the diffraction minimum. Note that there is a crossing point on which the curves intersect. It is determined by the growth of the total cross sections and, simultaneously, the growth of the slope of the scattering amplitude.

IV. RESULTS AND DISCUSSION

Now we have some tensions between the results of the TOTEM and ATLAS Collaborations at LHC all energies. This especially concerns the extraction of magnitudes of the total cross sections and $\rho(t = 0)$. New unique results of the ATLAS Collaboration do not improve the situation. The new ATLAS data present for the first time the results at very small momentum transfer. These first points and common difference between the ATLAS and TOTEM data will be crucial for the discussion of the total cross sections, rho-parameter, Odderon contributions, etc. Unfortunately, we found out that these points contradict the standard behavior of the electromagnetic amplitude. The analysis shows that the difference between the other points of ATLAS and TOTEM is related not with the behavior of the scattering amplitude but with different normalization only, which is very important for other studies.

Examining the new peculiarity in the differential cross sections of elastic scattering at LHC energies in a wide momentum transfer on the basis of all experimental data of the TOTEM-CMS and AlFA-ATLAS Collaborations, previously found in the differential cross section of the TOTEM Collaboration at 13 TeV [1, 2], strongly confirm the existence of these effects. Especially, we take only statistical errors which significantly reduce the corridor of the possible behavior of the scattering amplitude. The systematical errors are taken into account as additional normalization, which are equal for all points of the set.

FIG. 5. The $s$ and $t$ dependence of the imaginary (left) and real (right) parts of the elastic scattering amplitude (lines at small $t$ correspond top down to 13, 7, 2.96 TeV).
TABLE III. The $\sigma_{tot}(s)$ and $\rho(s)$ obtained in the HEGSh model

| $\sqrt{s}$ (GeV) | $\sigma_{tot}$ ATLAS | $\sigma_{tot}$ TOTEM | $\sigma_{tot}$ model | $\rho_{tot}$ ATLAS | $\rho_{tot}$ TOTEM | $\rho_{tot}$ model |
|------------------|----------------------|----------------------|----------------------|-------------------|-------------------|-------------------|
| 7                | 95.35 ± 2.1          | 98.5 ± 2.9           | 98.8 ± 1.4           | 0.145 ± 0.09      | 0.117 ± 0.03      |                   |
| 8                | 102.9 ± 2.3          | 101.7 ± 2.9          | 100.7 ± 1.4          | 0.12 ± 0.03       | 0.118 ± 0.04      |                   |
| 13               | 104.7 ± 1.1          | 110.6 ± 0.6          | 108.1 ± 1.4          | 0.098 ± 0.011     | 0.1 ± 0.01        | 0.119 ± 0.04      |

The magnitude of the constants of the effects is relatively large and is determined with small errors ($h_{fd} = 1.54 ± 0.08$ GeV$^{-2}$ and $h_{osc} = 0.37 ± 0.014$ GeV$^{-2}$), depending on the new ATLAS data at 13 TeV, and ($h_{fd} = 1.41 ± 0.07$ GeV$^{-2}$ and $h_{osc} = 0.36 ± 0.013$ GeV$^{-2}$), and taking into account the new ATLAS data at 13 TeV.

The HEGS model describes at a quantitative level the new experimental data at $2−13$ TeV $\chi^2_{dof} = 1.09$ without the new ATLAS data and $\chi^2_{dof} = 1.16$ with taking into account only statistical errors (see Fig.5). Such a description can be obtained only considering the new peculiarities of the elastic differential cross sections.

The new phenomena are determined by hadron interactions at large distances. The corresponding hadron potential has no simple exponential behavior. Our calculations [21] show that it has a modified Gaussian form with probably can be obtained only considering the new peculiarities of the elastic differential cross sections.

The new effects can impact the determination of values of the total cross sections, the ratio of the elastic to the total cross sections, and $\rho(s, t)$, the ratio of the real to imaginary part of the elastic scattering amplitude. As a result, we have obtained the values of $\sigma_{tot}(s)$ and $\rho(s)$ represented in Table 3.

It is very likely that such effects exist also in experimental data at essentially lower energies [22], but, maybe, they have a more complicated form (with two different periods, for example).

V. CONCLUSION

Our critical analysis of the new experimental data obtained by the ATLAS Collaboration group at 13 TeV shows that the first experimental points contradict the behavior of the electromagnetic amplitude at small momentum transfer. To remove such contradiction, it is necessary to take these points with large errors. The problem of tension between the ATLAS and TOTEM Collaborations data lies more part in different normalizations.

The analysis is based on all sets of experimental data of the elastic differential cross section in a wide region of momentum transfer confirms the existence of the new effects discovered on the basis of experimental data at 13 TeV [1, 2] and associated with the specific properties of the hadron potential at large distances. As a result, we have shown that the new peculiarities in the scattering amplitude are confirmed by all LHC data and are not artificial or instrumental effects of one experiment. The existence of such peculiarities is important for our understanding of the hadron interaction at large distances. Hence, it opens up a new direction in the study of hadron structure and interaction at super high energies and large distances.

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