Models of the hadron structure and Data of the TOTEM Collaboration

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The region of the small and large momentum transfer is examined from a viewpoint of the contribution of the different parts of the scattering amplitude, soft and hard pomeron, and odderon contribution. The new model taking into account the different moments of the General Parton Distribution of the hadron is presented. The comparison with the preliminary data of the TOTEM Collaboration at an energy of 7 TeV is made.

There are many different models for the description of hadron elastic scattering at small angles [1]. In the Chow-Yang model [2] it was assumed that the hadron interaction was proportional to the overlapping of the matter distribution of the hadrons, and Wu and Yang [3] suggested that the matter distribution was proportional to the charge distribution of the hadron. Then many models used the electromagnetic form factors of the hadron but, in most part, they changed its form to describe the experimental data, as was made in the Bourrely-Soffer-Wu model [4].

The differential cross sections of nucleon-nucleon elastic scattering can be written as the sum of different five helicity amplitudes. The total helicity amplitudes can be written as \( \Phi_i(s,t) = F_h^i(s,t) + F_{em}^i(s,t)e^{\varphi(s,t)} \), where \( F_h^i(s,t) \) comes from the strong interactions, \( F_{em}^i(s,t) \) from the electromagnetic interactions and \( \varphi(s,t) \) is the interference phase factor between the electromagnetic and strong interactions [5].

Our model is based on the representation that at high energies a hadron interaction in the nonperturbative regime is determined by the reggenized-gluon exchange. The cross-even part of this amplitude can have 2 nonperturbative parts, possible standard pomeron - \( P_{2np} \) and cross-even part of the 3-non-perturbative gluons - \( P_{3np} \). The interaction of these two objects is proportional to two different form factors of the hadron. This is the main assumption of the model. The second important assumption is that we chose the slope of the second term 4 times smaller than the slope of the first term, by analogy with the two pomeron cut. Both terms have the same intercept.

The form factors are determined by the General parton distributions of the hadron (GPDs). The first form factor corresponding to the first momentum of GPDs is the standard electromagnetic form factor - \( G(t) \). The second form factor, determined by the second momentum of GPDs - \( A(t) \), corresponds to the matter distribution of the nucleon [4] [7] [8]. The parameters and \( t \)-dependence of the GPDs are determined by the standard parton distribution functions, so by the experimental data on the deep inelastic scattering and by the experimental data for the electromagnetic form factors (see [9]).

Hence, the Born term of the elastic hadron amplitude can be written as

\[
F_{h}^{\text{Born}}(s,t) = h_1 \ G^2(t) \ F_0(s,t) \ (1 + \frac{r_1}{s^{0.5}}) + h_2 \ A^2(t) \ (F_0(s,t) \ (1 + \frac{r_2}{s^{0.5}}) + F_{\text{odd}}(s,t)) \ (1)
\]
where \( F_a(s, t) \) and \( F_b(s, t) \) has the standard Regge form

\[
F_a(s, t) = \hat{s}^{\epsilon_1} e^{B(s)/4} t; \quad F_b(s, t) = \hat{s}^{\epsilon_1} e^{B(s)/4} t; \quad F_{odd}(s, t) = \frac{it}{1/r_0^2 - t} \hat{s}^{\epsilon_1} e^{B(s)/4} t
\]  

(2)

with \( G(t) = G_E(t) \) being the Sachs electric form factor relative to the first moment of GPDs and \( A(t) \) relative to the second moment of GPDs.

\[
G(t) = \frac{L_1^2}{(L_1^2 - t)^2} \frac{(4m_p^2 - \mu t)}{(4m_p^2 - t)}; \quad A(t) = L_2^2/(L_2^2 - t)^2.
\]  

(3)

with the parameters: \( L_1^2 = 0.71 \text{ GeV}^2; \) \( L_2^2 = 2 \text{ GeV}^2. \) \( \hat{s} = s e^{-i\pi/2}/s_0; \) \( s_0 = 1 \text{ GeV}^2. \)

Figure 1: \( d\sigma/dt \) are calculated in the model for \( p\bar{p} \) at \( \sqrt{s} = 52.8 \text{ GeV} \) (with [hard line] and without [dashed line] odderon contributions) and for \( pp \) at \( \sqrt{s} = 23.4 \text{ and } 22.2 \text{ GeV}. \)

The final elastic hadron scattering amplitude is obtained after unitarization of the Born term. We have to calculate the eikonal phase and then obtain the final hadron scattering amplitude by integration of the eikonal of the scattering amplitude in the impact parameter representation.

Figure 2: a)[left] Comparison of the model calculations with the experimental data at \( \sqrt{s} = 7 \text{ TeV}; \) b)[right] \( d\sigma/dt \) are calculated in the model (long-dashed, hard, short-dashed, and dotted lines at \( \sqrt{s} = 7, 8, 10 \text{ and } 14 \text{ TeV}. \)

The first (simplest) variant of the model [10] has only 3 high energy fitting parameters and 2 low energy parameters, which reflect some small contribution coming from the different low energy terms. We check up the possible contribution of the hard pomeron [11]. We find that such contributions cannot see from the existing experimental data. Now in the slightly expanding
variant of the model we take into account the odderon contributions. We assume that the odderon, as cross-odd 3 gluon state, has the vertex with the second form factor $A(t)$. As we take low energy data, we include the small contribution of the hadron spin-flip amplitude in the simplest form. $F_{sf} = h_{sf} q_s * \exp[b_{sf}t]$. Now we take all existing experimental data in the energy range $20 \leq \sqrt{s} \leq 7000 \text{ GeV}$ and the region of the momentum transfer $0.0007 \leq -t \leq 15 \text{ GeV}^2$.

We do not include the data on the total cross sections $\sigma_{tot}(s)$ and $\rho(s)$. We also do not include the interpolated and extrapolated data of Amaldi. As a result, one obtains $\sum \chi_i^2/N \simeq 1.5$, where the number of experimental points $N = 2011$. The energy dependence of the scattering amplitude is determined only by the single intercept and the logarithmic dependence on $s$ of the slope. Now we obtain a good description for $pp$ scattering at $\sqrt{s} = 52.8 \text{ GeV}$ (Fig. 1(left panel)). At this energy there are experimental data at small (beginning at $-t = 0.001 \text{ GeV}^2$) and large (up to $-t = 10 \text{ GeV}^2$) momentum transfers. The model reproduces both regions and provides a qualitative description of the dip region for all energies (Fig. 1b).

We present the new model of the hadron-hadron interaction at high energies. As we know, it is the only model which describes all available high energy data in the Coulomb-hadron region and large momentum transfer. The model shows the contributions of the odderon with the same intercept as the pomeron. So it is the case of the maximal odderon. The energy dependence of the differential cross sections is determined by only one intercept with $\epsilon = 0.11$. The real part of the hadron scattering amplitude is determined only by complex energy $s$ that satisfies the crossing-symmetries. The most important advantage of the model is that it is built on some physical basis - two form factors which are calculated from GPDs. The model predictions for $\sigma_{tot}$ and $\rho$ are shown in Table 1. They well coincide with the existing experimental data before the LHC era.

| $\sqrt{s}$, GeV | $\rho(t = 0)$ | $\sigma_{tot}$, mb |
|-----------------|--------------|-------------------|
| 22.2            | 0.0013       | 39.85             |
| 52.8            | 0.076        | 42.85             |
| 541             | 0.128        | 62.91             |
| 1800            | 0.127        | 76.25             |
| 7000            | 0.121        | 95.9              |
| 8000            | 0.120        | 98.1              |
| 10000           | 0.119        | 101.6             |
| 14000           | 0.117        | 107.3             |

Table 1: The predictions of the model.

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References
[1] R. Fiore et al., Mod.Phys., A24: 2551 (2009).
[2] T.T. Chou and C.N. Yang Phys.Rev., 137 708 (1965).
[3] T.T. Wu and C.N. Yang Phys.Rev., 175 1832 (1968).
[4] C. Bourrely, J. Sofer, T.T. Wu, Eur.Phys.J. C28 (2003) 97.
[5] O.V. Selyugin, Mod. Phys. Lett. A9 1207 (1994); Phys. Rev. D60 074028 (1999).
[6] H. Pagels, Phys.Rev., 144 1250 (1966).
[7] M.V. Polyakov, Phys.Lett. B555 57 (2003).
[8] K. Goeke et al., Phys. Rev. D78 074003 (2008).
[9] O.V. Selyugin, O. Teryaev, Phys. Rev. D79 033003 (2009).
[10] O.V. Selyugin, Eur.Phys.J. C72 2073 (2012).
[11] O.V. Selyugin, Nucl.Phys. A903 54 (2013).