Models of elastic diffractive scattering to falsify at the LHC

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Abstract

The talk is a review of current situation with theoretical description of the soft elastic scattering at the LHC.

Introduction

Diffractive phenomena in hadron physics are related to strong interaction. QCD is recognized as the fundamental theory of strong interaction. Hence, the description of diffractive reactions at high energies should be grounded on some QCD-based techniques. But the special status of diffractive studies at high energy colliders is determined by the fact that diffraction of hadrons takes place due to interaction at large distances. Indeed, the transverse size of the hadron interaction region can be estimated through the corresponding Heisenberg uncertainty relation and the extraction of this quantity from the experimental elastic angular distributions can be done without dealing with any theory. For example, at SPS, Tevatron and LHC energies it turns out to be of order 1 fm. Technically, this means that we are in the so-called "non-perturbative regime" and straight applying of QCD to description of hadron diffraction is disabled, since QCD, at its modern stage, has no essential progress outside the perturbative calculations.

Hence, one is enforced to invent "plausible" models [1] – [21] which bear at least general QCD properties as much as possible.

Some of these models are called "QCD-inspired", some of them do not appeal to QCD at all. But all of them give predictions not only to global characteristics of the scattering process (such as the total cross-section, the zero peak slope or the position of the first diffractive dip) but also to behavior of the differential cross-section at low transferred momenta.

Scattering amplitude, Born term ("eikonal") and Regge trajectories

In the vast majority of models there is used the notion of reggeons – analytic continuations of the resonance spectra.

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Below the recipe for calculation of the elastic scattering amplitude in the framework of the Regge-eikonal approach [23] is presented:

$$T_{12\to 12}(s,t) = 4\pi s \int_0^\infty db^2 J_0(b\sqrt{-t})\frac{e^{2i\delta_{12\to 12}(s,b)}-1}{2i}\,,$$

$$\delta_{12\to 12}(s,b) = \frac{1}{16\pi s}\int_0^\infty d(-t)J_0(b\sqrt{-t})\delta_{12\to 12}(s,t) = \frac{1}{16\pi s}\int_0^\infty d(-t)J_0(b\sqrt{-t})\times$$
$$\times\left\{\sum_n\left(i+\mathrm{tg}\frac{\pi(\alpha_n^+(t)-1)}{2}\right)\Gamma_n^{(1)+}(t)\Gamma_n^{(2)+}(t)s^{\alpha_n^+(t)}\mp\right.$$
$$\left.\mp\sum_n\left(i-\mathrm{ctg}\frac{\pi(\alpha_n^-(t)-1)}{2}\right)\Gamma_n^{(1)-}(t)\Gamma_n^{(2)-}(t)s^{\alpha_n^-(t)}\right\}\,.$$

Here T is the elastic scattering amplitude, the eikonal δ is the sum of single-reggeon-exchange terms, $\alpha(t)$ are famous Regge trajectories and $\Gamma(t)$ are reggeon form-factors of colliding particles. At ultra-high energies only few terms in the eikonal survive and, so, the practical use of this approach is that in the case of high energy diffraction it allows to reduce the unknown function of two variables, $T_{12\to 12}(s,t)$, to few functions of one dynamical variable t (leading Regge trajectories and reggeon form-factors) and to make explicit estimations for the high energy evolution of the diffractive pattern.

The calculation of Regge trajectories within QCD is one of the main theoretical problems of hadron physics. What are fundamental achievements in this direction?

Regge trajectories and QCD

At present moment there exist two quantum field approaches yielding some results on QCD Regge trajectories. The first one is the famous BFKL approach based on solving the so-called BFKL equation – some modification of the Bethe-Salpeter equation. Within this approach the asymptotic behavior of Regge trajectories for reggeons composed of two reggeized partons was calculated for transfers of order 100 GeV and higher (in the case of quark-antiquark pair by Kwiecinski [24] and for two gluons by Kirschner and Lipatov [25]):

$$\alpha_{\bar{q}q}(t) = \sqrt{\frac{8}{3\pi}\alpha_s(\sqrt{-t})} + o(\alpha_s^{1/2}(\sqrt{-t}))\,,$$

$$\alpha_{gg}(t) = 1 + \frac{12\,\ln 2}{\pi}\alpha_s(\sqrt{-t}) + o(\alpha_s(\sqrt{-t}))\,.$$

As well, the intercept of the leading Regge trajectory, pomeron, was calculated by Fadin and Lipatov and, also, Ciafaloni and Camici [26]:

$$\alpha_{gg}(0) = 1 + \frac{12\,\ln 2}{\pi}\alpha_s(\mu)\left(1 - \frac{20}{\pi}\alpha_s(\mu)\right) + o(\alpha_s^2(\mu))$$

In contrast to the asymptotic relations at high transfers the last expression obtained in the MS-bar renormalization scheme is explicitly non-renorm-invariant since it depends on an arbitrary renormalization scale μ. It is unacceptable because Regge trajectories as analytic (i.e. unique) continuations of resonance spectra should be renorm-invariant. In the case of the BFKL-pomeron the intercept value can be made by particular choice of μ higher or lower than unity, and this result turnes out useless from the physical point of view. So, up to now the

BFKL method yields only asymptotic behavior of Regge trajectories at ultra-high values of the transferred momentum.

The second approach is the less-known Lovelace approach [27] which deals with the Bethe-Salpeter equation in some asymptotic regime where we do not need the reggeization of partons composing the considered bound state. The main feature of this approach is the exploitation of renorm-invariant kernels in the BS equation. As a result we obtain renorm-invariant numbers for intercepts of Regge trajectories. In his paper [27] Lovelace considered asymptotically free ϕ_6^3 theory and found some infinite series of intercepts:

$$(\alpha_{\phi\phi}^{(k)}(0)+1)(\alpha_{\phi\phi}^{(k)}(0)+2)(\alpha_{\phi\phi}^{(k)}(0)+3)=\frac{16}{3(2k+1)}\,.$$

In other two papers analogous results for gluon-gluon [28] and quark-antiquark [29] trajectories in QCD were obtained:

$$\alpha_{gg}^{(k)}(0)(\alpha_{gg}^{(k)}(0)+1)(\alpha_{gg}^{(k)}(0)+2)=\frac{24N_c}{(2k+1)(11N_c-2n_f)}\,,$$

$$\alpha_{\bar{q}q}^{(k)}(0)=\frac{9(N_c^2-1)}{(2k+1)N_c(11N_c-2n_f)}-1\,.$$

Unfortunately, due to technical difficulties the leading intercepts (corresponding to trajectories with Kwiecinski and Kirschner-Lipatov asymptotical behavior) were not calculated. So, at present moment we have got information about leading Regge trajectories at very high momentum transfers only. This region of transferred momenta, however, gives a negligible contribution to diffractive cross-sections. In other words, at current time QCD does not provide any quantitative result which could be directly used under construction of phenomenological models of hadron diffraction although some models try to adopt some qualitative QCD features.

Phenomenological models

The phenomenological schemes themselves could be divided into 2 groups – models exploiting the notion of reggeons [1, 2, 3, 4, 5, 8, 9, 10, 14, 15, 16, 17, 18, 22] and non-reggeon models [6, 7, 11, 12, 13, 19, 20, 21]. Each of them contains subgroups. In several reggeon models the eikonal representation of the scattering amplitude is used where the eikonal is the sum of single-reggeon exchange terms with a supercritical pomeron (or pomerons) as a leading term [4, 5, 18]. Other reggeon models do not use the eikonal representation but introduce some complicated leading Regge singularities (except the DL-model [22] using simple Regge poles only): the pomeron as a double Regge pole in [1, 2, 3, 8, 14], and the so-called Froissaron, the leading Regge cut, in [9, 10]. Also, these models take into account contributions from secondary Regge poles and cuts.

There exists a separate subgroup of reggeon models [15, 16, 17] exploiting methods of the Reggeon Field Theory. The eikonal here is replaced by the so-called opacity which is the sum of not only single-reggeon-exchange terms but also multi-reggeon exchanges. The low-mass dissociation in the intermediate states is taken into account.

The non-reggeon phenomenological schemes also can be divided into 2 subgroups: models not appealing to QCD [6, 12, 20, 21] and the so-called QCD-inspired models [7, 11, 13, 19]. The model [6] uses only general principles and the derivative dispersion relations as extra conditions. Models [12, 20, 21] are some variants of the quasi-potential approach.

In [7] the nucleon is considered to have an outer cloud, inner shell of baryonic charge and a central quark bag containing valence quarks (the small angle scattering is due to overlapping

The Model	$\sigma_{tot}^{pp}(7\,TeV)$, mb
P. Desgrolard, M. Giffon, L.L. Jenkovszky, Z.Phys. C **55** (1992) 637	87 (*6 TeV*)
P. Desgrolard, M. Giffon, E. Martynov, Eur. Phys. J. C 18 (2000) 359	95
V.A. Petrov, A.V. Prokudin, Eur. Phys. J. C 23 (2002) 135	97 ± 4
C. Bourrely, J. Soffer, T.T. Wu, Eur. Phys. J. C 28 (2003) 97	93
R.F. Avila, S.D. Campos, M.J. Menon, J. Montanha, Eur. Phys. J. C 47 (2006) 171	94
M.M. Islam, R.J. Luddy, A.V. Prokudin, Int. J. Mod. Phys. A 21 (2006) 1	97.5
E. Martynov, Phys. Rev. D 76 (2007) 074030	91
R.F. Avila, P. Gauron, B. Nicolescu, Eur. Phys. J. C 49 (2007) 581	108
E. Martynov, B. Nicolescu, Eur. Phys. J. C 56 (2008) 57	95
C. Flensburg, G. Gustafson, L. Lönnblad, Eur. Phys. J. C 60 (2009) 233	98 ± 9
P. Brogueira, J. Dias de Deus, J. Phys. J 37 (2010) 075006	110
M.M. Block, F. Halzen, Phys. Rev. D 83 (2011) 077901	95.5 ± 1
L.L. Jenkovszky, A.I. Lengyel, D.I. Lontkovskyi, Int. J. Mod. Phys. A 26 (2011) 4755	98 ± 1
E. Gotsman, E. Levin, U. Maor, Eur. Phys. J. C 71 (2011) 1553	91
M.G. Ryskin, A.D. Martin, V.A. Khoze, Eur. Phys. J. C 71 (2011) 1617	89
S. Ostapchenko, Phys. Rev. D 83 (2011) 014018	93
D.A. Fagundes, E.G.S. Luna, M.J. Menon, A.A. Natale, arXiv: 1108.1206 [hep-ph]	97
A. Godizov, Phys. Lett. B 703 (2011) 331	110
A. Donnachie, P.V. Landshoff, arXiv: 1112.2485 [hep-ph]	91
The TOTEM Collaboration, Europhys.Lett. 96 (2011) 21002	$98.3 \pm 0.2^{stat} \pm 2.8^{syst}$

Table 1: Comparison of the model predictions for the total pp cross-section at $\sqrt{s} = 7$ TeV with the TOTEM results.

of outer clouds and the exchange by ω-meson). In the Dipole Cascade Model [11] the nucleon is introduced as a color dipole and interaction between hadrons at ultra high energies is presumed to be dominated by perturbative effects. Models [13, 19] use the eikonal composed by 3 terms which are called contributions from the quark-quark, quark-gluon and gluon-gluon interaction although the corresponding expressions are not derived from QCD directly and contain numerous free parameters.

All the mentioned models give very different predictions for the total and differential pp cross-sections at the LHC.

Models vs. TOTEM

Comparison of the model predictions for the total pp cross-section with the value measured by the TOTEM Collaboration [30] reveals that some of the models may be judged as falsified already at this stage (Tab. 1). Though others survive.

However, some theorists may consider a deviation in several percents from the experimental data to be not fatal for any model. In any case, the measurement of the total cross-section does not allow the proper discrimination among the models.

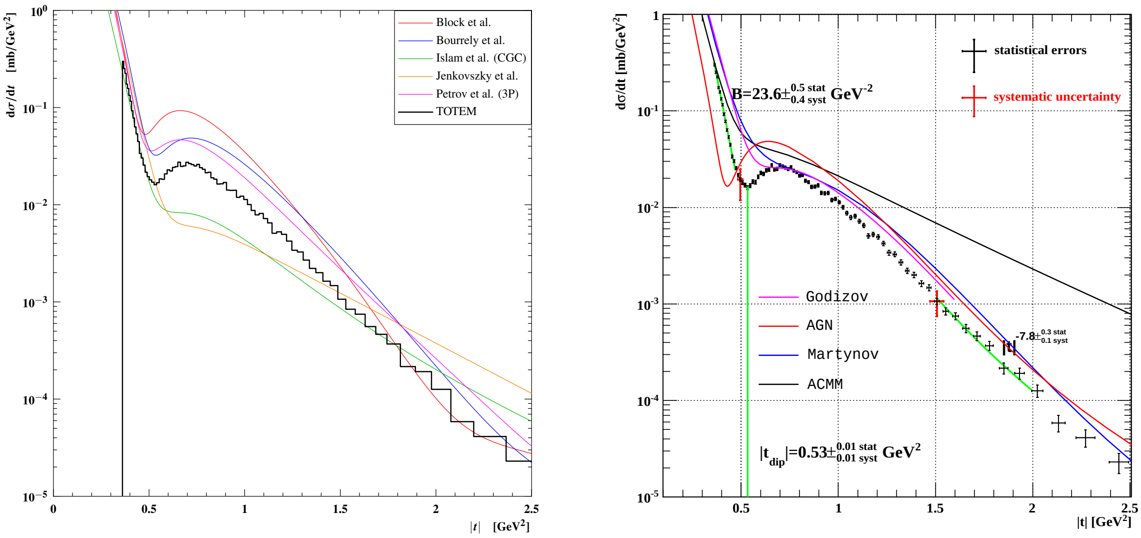

Figure 1: Comparison of the model predictions for the differential pp cross-section at $\sqrt{s} = 7$ TeV with the TOTEM results.

The TOTEM data on the *pp* differential cross-section [31] reveal a very strong discriminative power (Fig. 1). Inversely, the predictive power of all the considered models turnes out very weak. I mean the fact that many of these models give a nice description of differential cross-sections from ISR to Tevatron energies [32] (with the collision energy increase in several tens of times). But though the ratio of the LHC energy to Tevatron energy is less than 4, we can observe a huge discrepancy between model curves and the data (for some models tens of percent, for others several times).

Another question: what are the consequences of such a result for QCD? Is it falsified? Certainly, no. The picture is quite different from that one for the electroweak physics where discovery or undiscovery of the light Higgs boson will either confirm the theory or cause some fundamental changes in it. Vice-versa, in the case of hadron diffraction only phenomenological models are subjects of falsification but QCD is not. Such a situation takes place due to the fact that all diffraction models are not grounded on analytical derivations from QCD, though some of them use adopted QCD terminology. Of course, in the nearest future the most of models will experience internal parametric complications and after tuning the enlarged set of parameters they will describe the TOTEM data more or less satisfactorily. But who can guarantee that such a situation will not be reproduced after measurements at 14 TeV?

Conclusion

We need a deeper interrelation of phenomenological models with QCD. This requires developing powerful non-perturbative QCD techniques which should allow to deal with diffractive (large distance) domain of strong interaction.

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