Diffractive scattering: problems in theory and practice

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Abstract. We give a retrospective overview of the conceptual content of the strong interaction scattering at high energies with account of the latest experimental findings made at the LHC.

1. Introduction
All experiments which are being performed at the LHC can be roughly divided into two classes: “Old Physics” and “New Physics”. “Old physics” comprises any kind of measurements to complete the Standard Model (the brightest example is the Higgs discovery) while “New Physics”, starting from the evidently vital and pressing problems like neutrino masses, but extends much far away with searches for supersymmetry, “stringy” effects, dark matter, leptoquarks, compositeness ant even further: micro black holes and extra dimensions of space-time. “New physicists” are obsessed with a dream to find at least some sort of exotic. However, the years pass, more and more powerful machines come into operation and upgrade: ISR, Tevatron, $S\bar{p}pS$, LEP I, LEP II, at last LHC but no signatures of something fundamentally breaking the SM paradigm appear. Does it mean that what we really observe today can be referred as a boring, “Old Physics” stuff? It is true that the Standard Models leaves many questions about its architecture and composants asking for a new theoretical basis. Yet the very SM is actually a new, relatively recently born discipline, like electrodynamics just after the Maxwell equations were formulated. Similarly to the first period of the electrodynamics development we have to wait for a lot of new effects. This asks for a thorough and concentrated efforts and one should decide which part of financial means, intellectual and technical forces should be devoted to the the searches in “Old Physics”. At the moment there is an impression that too much of (always limited) resources is being spent for obtaining invariably negative results in the searches for, often quite ill-founded, fantasies of imminent “gurus”. In this talk I would like to tell about a specific part of the Standard Model, namely the strong interactions at high energies. Their salient features are revealed best in diffractive scattering.

2. What is diffractive scattering?
At Fig. 1 the angular distribution of the light scattering off a polystyrene latex particle is shown. The energy of the incident photons is $\approx 2.5\text{eV}$. The size of the particles-scatterers is near $0.3\mu \text{m} = 3 \cdot 10^8 \text{fm}$.

Let us compare this pattern with that of the proton-proton scattering at Fig. 2. This time the energy of collision is much higher: $10^{11} \div 10^{12}\text{eV}$ while the effective scatterer size is of order
We see that at such huge difference in energy and scatterer sizes the diffraction angular distributions are very similar.

Why should we study the diffraction in the proton-proton collision at powerful accelerators if we can observe it at much less costly facilities? Moreover, why to study elastic scattering when “nothing happens” except the deviations of the colliding protons after their mutual “shock” akin to billiard balls we can play in a pub? There are several reasons.

First of all protons aren’t hard balls. According to our present views the proton consists of the “valence” core comprised of three quarks (u,u,d) which swim in the “sea” of permanently changing quantum fluctuations consisting of arbitrary number of quark-antiquark pairs and gluons. The average size of the valence quark core is fixed while that of the “sea” is not Lorentz invariant and depends on the momentum of the proton. Moreover the latter expands with the energy growth and at some energy comes outside and continues to grow as pictured in Fig. 3.

This fact makes the proton diffraction picture qualitatively different from that of the
diffraction picture of the light scattering off a polystyrene latex particle. With the energy growth the position of the diffractive minimum slowly moves to the left. Starting at the ISR at $-t = 1.4 GeV^2$ it achieves the value near $0.5 GeV^2$ at the LHC. Namely this feature reflects the complicated quantum structure of the proton and explains why we should study this seemingly simple process.

3. Interaction region

Actually the characteristic size of the effective scatterer — normally called “interaction region” —is defined not from the position of the minimum in the angular distribution of the scattered protons but from some derivative of the differential cross-sections $d\sigma/dt$, the “forward slope” $B(s)$ defined as

$$B(s) \equiv \frac{1}{d\sigma/dt} \left. \frac{\partial [d\sigma/dt]}{\partial t} \right|_{t=0} = \left. \frac{\partial \ln[d\sigma/dt]}{\partial t} \right|_{t=0}$$

Physical meaning of this quantity is given by the relation $2B(s) = \langle b^2 \rangle$ where $b$ is the impact parameter of the collision. So the experimentally observable quantity $B(s)$ defines the size of the interaction region, i.e. the region outside of which scattered particles move away freely. The growth of the interaction size mentioned above proceeds extremely slow. For instance, at the energies of the Protvino proton synchrotron U-70 (0.01 TeV) $\langle b^2 \rangle^{1/2} \approx 0.9 fm$ while at the highest present energies of the LHC ($O(10 TeV)$) $\langle b^2 \rangle^{1/2}$ achieves only 1.3 fm. What can we learn from observation of the forward slope evolution at Fig. 4? The point indicated by

![Figure 4](image_url)

Figure 4. Energy evolution of the transverse interaction region [4].

the arrow at Fig. 4 is obtained at $\sqrt{s} = 2.76 TeV$ and shows $B = 17.2 GeV^{-2}$. The energy evolution of $B(s)$ at lower energies looks as it points a linear log dependence on energy. But at higher energies (7 TeV and higher) the values of $B$ jump to $B \geq 20 GeV^{-2}$. So, something happens at energies near 2.5 – 3 TeV. At the moment we can only guess but one thing deserves our attention. If we calculate the 3D length corresponding to its 2D projection given by $B$ we obtain exactly the pion Compton length $1/m_\pi$! Thus, if this results will be finally confirmed,
we have to conclude that some mysterious change of the interaction regime happens between 2.5 and 3.0 TeV.

The behaviour of the longitudinal interaction region is also very unusual. Contrary to naive expectations of compression of all longitudinal sizes in the direction of the colliding proton beams we actually deal with a fast (∼√s) growing size achieving the values of order of 10^3 fm at the LHC. Only this example shows how interesting field is diffractive scattering at high energies.

4. What theory gives?
Since the beginning of 1970s the basic theory of strong interaction is QCD. It would be naive to expect that somebody would be able to derive the exact strong-interaction S matrix from the QCD Lagrangian. But some important ingredients could be the subject of the QCD studies. I mean the famous Regge trajectories which define the energy dependence of the observed cross-section. If T(s,t) is the scattering amplitude then in a rough approximation its energy and angular dependence is given by ∼ s^α(t). The main interest is related to a special trajectory αP(t), the Pomeron, which has the highest “intercept”, αP(0) defining the behaviour of the total cross-sections. Unfortunately, QCD “works” well only at very high Euclidean momenta, −t ≫ mass^2 in our case. It was shown by R. Kirschner and L. N. Lipatov [3] that in this limit

\[ \alpha_P(t) \approx 1 + 4N_c ln2/\pi \cdot \frac{g_2(t)}{4\pi} + ... \]

where \( \frac{g_2(t)}{4\pi} \sim 1/ln(-t/\Lambda^2) \) according to the famous asymptotic freedom property of QCD. Some general considerations imply that Regge trajectories should be monotonic functions and this leads us to an important conclusion: \( \alpha_P(0) > 1 \). This means that the total cross-section indefinitely grow with energy. Unfortunately, this qualitatively important fact still cannot find its quantitative embodiment: the calculation of the numerical value of the Pomeron intercept \( \alpha_P(0) \) remains on the agenda already 40 years! Thus the study of the diffractive scattering is tightly related with the most fundamental problem of QCD behaviour at large distances, which are, in turn, unavoidably related to the seminal confinement problem.

5. Conclusions
I would like to quote from the New Testament the question of Saint Peter to Jesus Christ “Quo vadis, Domine?” We also can ask the High Energy Physics: “Where are You going to?” And there are two ways to go: inside (the most of the SM and beyond the SM) or outside (strong interactions at high energies). Both directions are important, we should not underestimate each of them.

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References
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