

Hadron Diffraction: Results and Problems

Vladimir Petrov^{1,*}

¹*Institute for High Energy Physics NRC Kurchatov Institute, 142281, Protvino, RF*

Abstract. This is a cursory review of diffractive studies at the LHC with physical interpretation of the experimental data and related problems of theory.

1 Introduction

What is hadron diffraction? We mean under this term a class of processes in hadron-hadron collisions which are characterized by specific angular distribution of the scattered particles similar to diffraction patterns in optics and by the mating feature: large rapidity gaps. The particles to be detected are produced at small angles w.r.t. the colliding beams. Why are such studies worthy of being made? Which fundamental problems of modern physics can be resolved with help of the corresponding data? In terms of characteristic spatio-temporal scales diffractive studies deal with distances and times much larger than those which characterize the majority of the LHC experiments, e.g. the Higgs or hard jets production. Moreover, this difference gets more drastic with the energy growth. When we say "larger" we mean "larger or even significantly larger than 1 fermi". Well, such distances are a routine feature in low-energy nuclear physics. Why expend energy to rediscover them again? The matter is that 1 fm at 100 MeV grossly differs from 1 fm at 1 TeV. In what follows we try to show this exposing the latest results obtained in diffractive studies at the LHC and trying to understand their physical meaning.

2 A Bit of History

One of the most claimed quantities in high-energy physics is total cross-section σ_{tot} as function of energy, $\sqrt{s} = 2\sqrt{p^2 + m^2}$ in the center-of-mass frame (p is the c.m.s momentum of the colliding protons and m is the proton mass). This quantity is often loosely described as "an effective area" (transverse to the beam(s)direction) where something happens with colliding hadrons. The formal definition is

$$\sigma_{\text{tot}} = \sum_X \sigma_X, \quad (1)$$

where σ_X is the cross-section of any possible process $p + p \rightarrow X$. "Optical theorem" states that the total cross section is simply related with the imaginary part of the amplitude of elastic scattering $p + p \rightarrow p + p$:

$$\sigma_{\text{tot}} \cdot 2p \sqrt{s} = \lim_{\theta \rightarrow 0} T(s, t), \quad (2)$$

*e-mail: Vladimir.Petrov@ihep.ru

where $t = -2p^2(1 - \cos\theta) \approx p^2\theta^2$. We carefully use the symbol *lim* to stress that zero-angle scattering doesn't mean that "nothing happened". With no massless exchange particle a non-trivial limit exists. The optical theorem shows that the total cross-section is not only a geometrical quantity but is also defined by the intensity of interaction embodied in the amplitude. Some 50 years ago physicists believed that at very high energies total cross-sections achieve a limiting constant value naturally defined by a "strong interaction radius" $\sim m_\pi^{-1}$. The only dissident was W. Heisenberg who predicted $\sigma_{tot} \sim \ln^2 s$. However his derivation was discarded by fellow theoreticians like Landau et al. for years to come. When in 1971 experiments at the 70 GeV "Serpukhov" proton synchrotron in Protvino showed that the cross-section of interaction of the K^+ -meson with the proton *grows* with energy experimentalists decided that this is but a transitory effect and finally the constant value will be achieved. In two years the story had repeated at the CERN ISR, this time with the proton-proton cross-section and at energies five times higher. Physicists were very much embarrassed but desperate attempts of theoreticians to save the asymptotic constancy failed one after another. For the sake of fairness we have to notice that 18 years since the Heisenberg paper two bold theorists T. T. Wu and H. Cheng published a paper where they predicted, in the framework of some specific model, the asymptotic growth of the total cross-sections $\sim \ln^2 s$ though their arguments differed from those by Heisenberg. The experimental discovery of the growth of the total cross-sections was not the discovery of exactly logarithmic growth - other options had (and have) enough room - and it posed a difficult problem before the theorists: why and how do cross-sections grow? We will touch this problem below but now I would like to come directly to the latest available results from the LHC.

3 LHC: Diffractive Products[1].

3.1 Integral Cross-Sections: Total, Elastic and Inelastic .

Since the operation of the ISR no new data on the total cross-sections in pp interactions were available. Due to known similarity of pp and $\bar{p}p$ we relied on the results in $\bar{p}p$ obtained in $S\bar{p}pS$ at CERN and *TEVATRON* at Fermilab. "For sake of poverty" the cosmic data were also in use in spite of huge errors. These partially surrogate data indicated that cross-sections continue to grow. So, generally it was not a great surprise when first LHC measurements revealed that σ_{tot}^{pp} have grown at energies two orders of magnitude higher than those at the ISR though the growth in cross-sections was only slightly more than two times. Nonetheless I would like to emphasize that this result cannot be considered as a routine one or so because even with account of the $\bar{p}p$ and cosmic ray data σ_{tot}^{pp} could go quite in different ways, up to the flattening. As $\sigma_{tot} = \sigma_{el} + \sigma_{inel}$ the growth of the total cross-section does not necessary lead to the growth of both σ_{el} and σ_{inel} . So the discovery made by the TOTEM Collaboration that both σ_{el} and σ_{inel} (confirmed afterwards by ATLAS and, in regard to inelastic cross-sections, by the CMS and ALICE Collaborations) grow seems quite non-trivial. Moreover, not only σ_{el} grows absolutely but the ratio $\frac{\sigma_{el}}{\sigma_{tot}}$ has also grown from 18 percent at the ISR to 27 percent at the LHC. In simple words, the more is the relative velocity of colliding protons the less they "want" to give up their energy for inelastic processes. If this trend will persist till the full dominance of elastic scattering or it will finally stop or changed for the opposite? This is a very exciting and pressing problem. Certainly, answers of the type "they grow because parameter $\Delta = 0.08$ " is not what we mean.

3.2 Interaction Radius Grows with Energy

Experiments at the ISR revealed the appearance of the dip in $\frac{d\sigma^{pp}}{dt}$ at $\approx 1.3 \text{ GeV}^2$ (the onset of it was "felt" already at the Serpukhov synchrotron). The dip (minimum) is a typical diffractive feature

inherent to all ondulatory phenomena due to interference. Its position is inversely proportional to the square of something which can be vaguely called "interaction radius". TOTEM has found that the dip moved closer to zero and arrived to $\approx 0.5 \text{ GeV}^2$ at 7 TeV. Thus the interaction radius grows with energy. We have to keep in mind that this is not equivalent to the growth of the cross-sections. A similar phenomenon was observed by TOTEM for the so-called forward slope whose growth also signals the growth of the interaction radius. And again both phenomena are not the same.

3.3 $\frac{d\sigma^{pp}}{dt}$ at Small Transferred Momenta: Simple or Complicated?

Gaussian form $\exp Bt$ for $\frac{d\sigma}{dt}$ in many cases appeared quite adequate but already at the ISR energies it was noticed that more complicated form $\exp(Bt + Ct^2)$ is not ruled out. Such a conclusion has been strengthened by the observation made by TOTEM that at the level of 7σ the t-distribution should be described by $\exp(Bt + Ct^2)$ or even by $\exp(Bt + Ct^2 + Dt^3)$. It is not easy to interpret such a finding in simple non-formal terms. We can only say at the moment that different forms shown above are related with different forms of the "profiles" in the impact parameter space. Furthermore, it's probable that alternative forms can be invented to describe the data no worse than these exponentials or combinations of them.

3.4 How to Find out the Phase ?

Protons are electrically charged and so it is impossible to get rid off the ubiquitous photons both surrounding the colliding protons and exchanged between them. This leads to a specific phenomenon of the Coulomb-nuclear interference: there exists the region of t where Coulomb and strong ("nuclear") interactions are comparable. At lower transfers the Coulomb part absolutely dominates, at higher ones it dies-off giving the floor to the strong interactions. In the narrow interval of transfers the interference term is directly related to the phases of both participants. As to the Coulomb phase (without strong interactions) it can be calculated theoretically. Another case is the strong interaction phase. At the moment no feasible model exists for it. Those which dominated the "market" during several decades should be ruled out as theoretically inconsistent. So the measurements provided by the TOTEM Collaboration on this subject are very valuable and are directly related to the possibility of the extraction of the phase from the data (even if only in a limited interval of t and with a certain degree of model dependence). The information on the strong interaction phase is extremely important for our understanding of the spatial character of the high-energy collisions : are they more central or more peripheral?

4 Where is QCD?

Up to now all model predictions failed to describe the data on the differential cross-sections measured by TOTEM, especially near the dip and to the right of it. However, the failure of models (some or even all of them) is not a conceptual disaster : after some repair the models try to cope with data again and this process repeats itself already during several decades. Certainly we would like to have something more fundamental to compare with the data, something the failure or success of which would mean much for our world view. LHC experiments successfully test the Standard Model in its electroweak part with a crucial result on the Higgs existence. Strong interaction part of the Standard Model is embodied in quantum chromodynamics(QCD). Can we test QCD in diffraction experiments? Everybody knows that QCD is a weakly coupled theory when applied to the processes

characterized by short distances with all pleasures of perturbative calculations. At which distances do occur diffraction processes? Alas, in this case the characteristic spatial scales, as was mentioned in the Introduction, are by no means small. Even worse, they grow with energy. And we are standing before the great problems of QCD at large distances which are very far from being resolved. As realists, we understand that it is quite silly to hope that QCD can give us some exact results on the scattering amplitude of such complicated composite objects like protons. But we can fairly hope to use QCD for obtaining at least a few important parameters, such as the intercepts and the slopes of leading Regge trajectories. This could help us to understand, both quantitatively and qualitatively, the gross features of diffractive processes at high energies.

And at last we, theorists, have to thank our fellow experimentalists for giving us so rich food for our minds.

Acknowledgements

I am grateful to the Organizers of QUARKS-2016 for invitation and very good organization of the seminar.

References

- [1] TOTEM Collaboration, *Europhys. Lett.* **101**, 21002, 21004(2013) ;
Phys. Rev. Lett., **111**, 012001 (2013);
ATLAS Collaboration, *Nucl. Phys.* **889B**, 486 (2014);
CMS Collaboration, *Physics Letters* **B722**, 5 (2013);
ALICE Collaboration, *Eur. Phys. J. C* **73**, 2456 (2013) .