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Several Effects Unexplained by QCD

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Abstract: Several new experimental discoveries in high energy proton interactions, yet unexplained by QCD, are discussed in the paper. The increase of the cross sections with increasing energy from ISR to LHC, the correlation between it and the behavior of the slope of the elastic diffraction cone, the unexpected increase of the survival probability of protons in the same energy range, the new structure of the elastic differential cross section at rather large transferred momenta (small distances) and the peculiar ridge effect in high multiplicity inelastic processes are still waiting for QCD interpretation and deeper insight in vacuum.

Keywords: proton; quark; gluon; QCD; vacuum; cross section

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1. Introduction

Cosmic-ray studies revealed many new unexpected features of particle interactions. The invention of particle accelerators and, later on, colliders helped to learn paticle properties in more detail. Nowadays higher energy results come out from the Large Hadron Collider (LHC). Proton beams collide there with energy $\sqrt{s}$ up to 13 TeV in the center-of-mass system that exceeds their own rest mass by more than 4 orders of magnitude. The main goal of the particle studies (and, in particular, those at LHC) is to understand the forces governing the particle interactions and the internal structure of the fundamental blocks of matter[1]. These forces (electroweak and strong) are united now within their common theory—the so-called Standard Model.

Many bright phenomena were observed since early days of particle physics. Two events must be specially emphasized—the 1983 discovery [1] at the Super Proton Synchrotron (SPS) of the intermediate vector bosons $W^{\pm}$ and Z^0 with masses of about 80 and 91 GeV, mediators of the weak interaction, and the 2012 discovery [2,3] at the LHC of the final scalar piece of the Standard Model—the Higgs boson with mass of about 125 GeV. It validates the Standard Model and shows a right way to understanding the cornerstone problem of the origin of masses of some fundamental particles and constituents of matter. Nowadays, studies of Higgs properties and searches for supersymmetry formed the mainstream of interests in particle physics.

In the meantime, the data coming from the Large Electron-Positron collider (LEP) and the Deutsches Electronen-Synchrotron (DESY) strengthened our belief in a particular piece of the Standard Model—the theory of strong interactions Quantum ChromoDynamics (QCD). They showed the existence of quark and gluon jets in e^+e^--annihilation and revealed the partonic content of protons in their interactions with electrons. It looks as if we know already the general laws which govern the

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1 Recall that the proton is the hydrogen nucleus and the electric charge of any atomic nucleus is determined by the number of protons in it.

interactions of proton's constituents—quarks and gluons. Nevertheless, "The knowledge of general laws of physics does not necessarily imply the understanding of a particular phenomenon" [4] as L.D. Landau said in one of his popular lectures.

Some phenomena, which are hard to interpret, will be described and discussed below. The observed effects lie in the domain of the strong interaction forces and should be explained by QCD. However there is a lack of mathematical tools and physics approaches which would explain them now.

The most widely used theoretical method in physics is the perturbative approach with its power series expansion using the smallness of the coupling constant. It can be applied in QCD only for collisions with large transferred momenta (or high masses) where the coupling strength becomes small due to the asymptotic freedom property. It happened to be successful for jet processes, briefly mentioned below, and for branching ratios of heavy resonances produced in high-energy collisions.

Unfortunately, the perturbative calculus does not work for the main bulk of soft hadron interactions with low transferred momenta, where the coupling constant is large enough and the non-perturbative approach must be applied. The new mathematical methods and physics models were developed for description of soft processes. Some of them (for example, Wilson loops and reggeon models) are very helpful. Even then, the knowledge of the dynamics laws (the QCD Lagrangian) does not necessarily imply immediate understanding of the QCD vacuum properties. Namely they are probably at the origin of many effects discussed below. Phenomenological models are mostly used to describe the experimental characteristics, and many adjustable parameters are introduced in these models. That makes their predictions very flexible and less definite. Some (rather limited) help can be gained from the general principles of analiticity and unitarity of the scattering amplitudes. QCD input and deeper insight in vacuum properties are strongly requested.

Some relevant experimental results about proton interactions and their implications are discussed below.

2. The Energy Behavior of the Cross Sections

The physics results obtained at fixed-target accelerators dominated till 1970s. The proton-proton total cross section was steadily decreasing with energy increase. From personal talks with my tuitor I.Ya. Pomeranchuk at the end of 1950s I remember him saying that theorists believed that it will decrease further similarly to the cross section of the electron-positron annihilation or tend asymptotically to a constant value related to the proton sizes of the order of 1 fm. This belief was first strongly shuttered in 1971 [5] by measurements at the fixed-target Serpukhov accelerator at energies up to $\sqrt{s} \approx 12$ GeV in the center-of-mass system. The measured cross section of the interaction of positively charged kaons (K^+) with protons started to increase by several percents at energies[2] from 8 to 12 GeV. At the very beginning this observation asked for its confirmation. This effect became well recognized in proton-proton collisions after being confirmed by the rise of their total cross section by about 10% in the wider energy range from about 10 to 62.5 GeV at the Intersecting Storage Rings (ISR) collider [6,7]. Nowadays, a much stronger effect is clearly seen at LHC up to 13 TeV as demonstrated in Figure 1 for total, inelastic and elastic cross sections. The total cross section increases more than 2.5 times from ISR to LHC. Cosmic-ray data obtained by two collaborations Auger and Telescope Array support this tendency up to higher energies almost 100 TeV albeit with much less precision. They are also shown in Figure 1.

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[2] It is interesting that at the same energies the slope of the elastic diffraction cone drastically changes its energy dependence and the real part of the forward scattering amplitude passes through zero changing its sign as discussed in the Section 3 below.

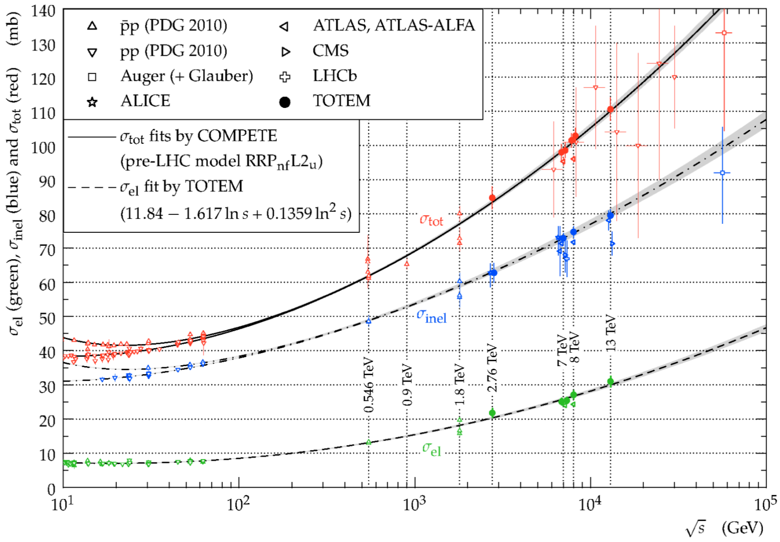

Figure 1. The energy dependence of the total, elastic and inelastic proton-proton cross sections [8].

Such a behavior means that the transverse size of the interaction region of protons becomes larger at higher energies. An upper bound on the increase of the total cross section was theoretically imposed when it was shown that it cannot increase more rapidly than the logarithm of the energy to the second power (Froissart-Martin bound [9,10]). However, the coefficient in front of the logarithm is large so that, phenomenologically, this bound does not exclude, at present energies, the use of a slow power-law energy dependence within the imposed upper limit. It was shown that simplest approximations of the QCD-approach with the two-gluon exchange can lead to the power-law behavior [11]. The rise of hadronic cross sections is understood within scattering theory as being due to a virtual exchange of vacuum quantum numbers, known in Regge theory as a Pomeron (for a review see [12]). The power-like dependence can be ascribed to the exchange of the so-called supercritical Pomeron, i.e., the pole singularity with intercept exceeding 1. The very existence of such Pomeron or other suitable Reggeon singularity as well as their dynamical origin are still debated.

3. The Energy Behavior of the Ratio of Elastic to Total Cross Section

If the behavior of the total cross section can be phenomenologically interpreted in terms of reggeon exchanges, the yet unsolved puzzle is provided by the energy dependence of the ratio of the elastic cross section to the total cross section (the survival probability[3] of protons). It is shown in Figure 2 that this ratio is also increasing from ISR to LHC by more than 1.5 times. In other terms, the inelastic cross section is about 5 times larger than the elastic one at ISR while it becomes less than 3 times larger at LHC energies.

The ordinate axis of Figure 2 tells us that the survival probability of protons to leave the interaction region intact is high enough and, what is more surprising, increases at higher energies. In other words, even being hit at higher energy, they do not break up producing secondary particles in inelastic collisions but try to keep their entity. Naively, one could imagine the protons as two Lorentz-compressed bags colliding with high velocities. The bag model was widely used for describing the static properties of hadrons with quarks and gluons immersed in a confining shell. The color forces between the constituents are governed by QCD. Somehow, Nature forbids the emission of colored objects - quarks and gluons. Thus these constituents can be created only in colorless combinations

[3] In a wider meaning, this term was used as the probability of large rapidity gaps for jet (or high masses) production and for low-mass diffractive excitations of colliding protons [13–15]. The rapidity gap between the elastically scattered protons is the largest one.

manifested as newly produced ordinary particles in inelastic collisions. The dynamics of internal fields during collisions and color neutralization is yet unclear. However they and their quantum origin must be responsible for the observed increase of the survival probability.

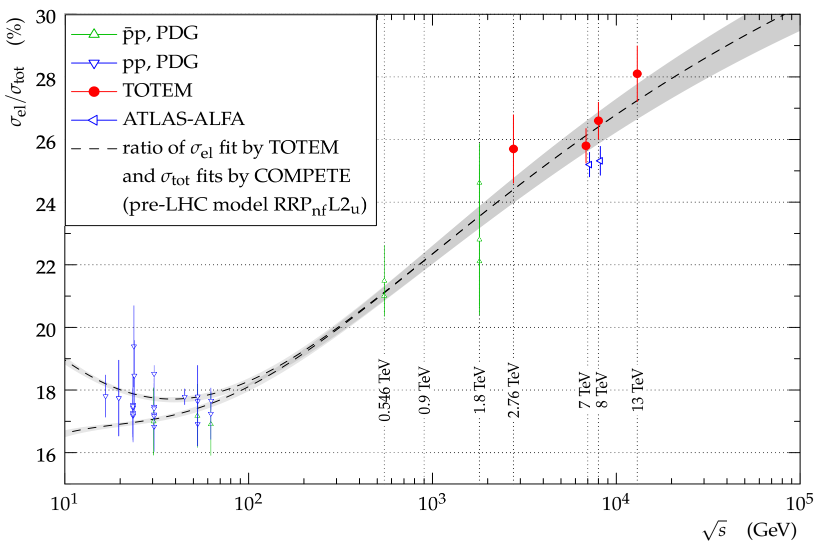

Figure 2. The energy dependence of the ratio of the elastic to total proton-proton cross sections [8].

One is tempted to relate the increasing survival probability to the relativistic longitudinal shrinkage of the colliding objects in combination with the confinement property and the asymptotic freedom. Short distances are probed by the highly virtual spacelike quanta—gluons. Their impact is suppressed because of the smallness of the coupling constant of QCD. It could be partly compensated by soft gluons when the product of the coupling constant and the logarithm of their (share of) energy enters the evolution equations. At large gluon densities of the relativistically compressed fields, protons can be approximated by coherent gluon fields with multiple reggeized gluon exchanges known as the color glass condensate (CGC) [16]. Somehow, the whole picture recalls the high speed bullet passing through a thin sheet of glass and leaving just a small hole without any cracks. The confinement property of QCD heals the wound. Thus the second proton also stays intact.

Some other hypotheses based, in particular, on assumptions about the strengthened bag envelope or on CGC and its relation to the superfluidity property are discussed in the Ref. [17]. At the deeper level, all of them suffer from poor knowledge of some intricate features of multilayered QCD vacuum.

4. The Elastic Differential Cross Section

Some new interesting features were noticed in the shapes of the differential cross sections of elastic scattering both at low and comparatively large transferred momenta.

The dependence of the elastic differential cross section on the transferred momentum is important for understanding the global features of the internal structure of protons. For small angular deflections, the momentum transfer can be low enough so that a wave description becomes appropriate. The corresponding wavelength (inversely proportional to the momentum transfer) becomes similar to the dimensions of the proton and the resulting diffraction pattern (i.e., angular distribution) reveals this dimension. A hard scattering (i.e., large momentum transfer) implies a deeper penetration inside protons and some possibility to learn their internal structure (as first pointed out by Rutherford [18]).

At small scattering angles θ the shape of the differential cross section $d\sigma/dt$ can be approximately described by a Gaussian in angles or a simple in the transferred momenta exponent (see Figure 3). It is quite well fitted by various phenomenological models using mostly the reggeon approach [12]. The slope B of the diffractiom peak $d\sigma/dt \propto \exp(Bt)$ (where $-t = 2p^2(1-\cos\theta) \approx p^2\theta^2$, p is the c.m.s. momentum of colliding protons) equals the squared size of the proton. As discussed above, the protons grow in size at higher energies. The height of the cone grows in accordance with the energy dependence of cross sections shown in Figure 1, its width shrinks so that the slope gets steeper at higher energies. According to the reggeon approach the slope B should increase with energy logarithmically $\propto \ln s$. Its energy dependence measured experimentally is shown in Figure 4.

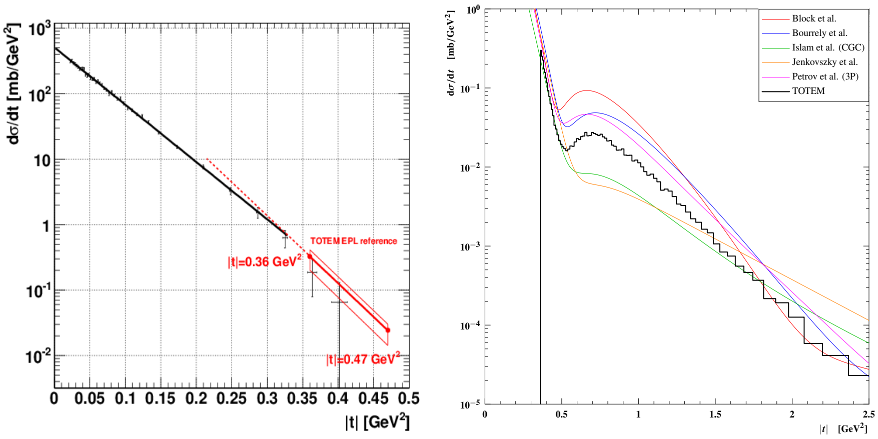

Figure 3. The differential cross section of elastic proton-proton scattering at the energy $\sqrt{s}$ = 7 TeV measured by the TOTEM collaboration. **Left**: The region of the diffraction cone with the $|t|$-exponential decrease [19]; **Right**: The region beyond the diffraction peak [20]. The predictions of five models are demonstrated.

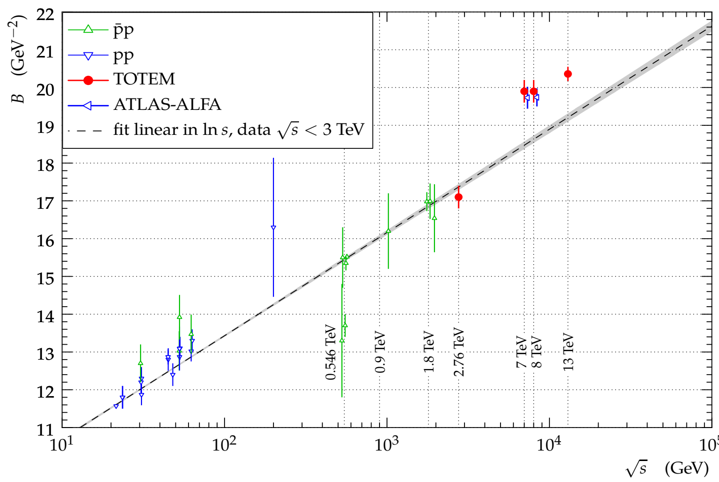

Figure 4. The energy dependence of the slope B of the diffraction cone [8].

The data at higher LHC energies lie above the simple logarithmic straight line drawn in Figure 4. It looks as if the rate of the growth also increases. That violates the single-pole reggeon prescriptions. The typical size of the hadron interaction region, still being about 1 fm, grows with energy increase (see Figure 7 below).

There exists the intriguing correlation between the energy dependences of the total cross section and of the slope of the diffraction cone in a wide interval of energies. Both of them drastically change their behavior at energies of about 10 GeV. The total cross section passes its minimum and starts increasing as shown in Figure 1. The slope changes its fast (almost linear at lower energies) increase with energy to much slower (logarithmic) dependence shown in Figure 4. The relation of this correlation with the spatial picture of proton interactions is discussed in [21].

It is interesting that the real part of the forward elastic scattering amplitude changes its sign from a negative to a positive one just at the same energy. This change has been shown from the measurement of the interference between the nuclear and Coulomb contributions to the differential cross section. Actually, this effect was predicted earlier in studies of the dispersion relations [22–24]. According to the general analytical properties, the real part of the forward scattering amplitude is represented as an integral of the forward imaginary part (i.e., of the total cross section, due to the optical theorem), and therefore can be calculated. The real part was predicted to be small inside the cone at high enough energies. That is now confirmed by experimental data [25]. The ratio of real to imaginary part of forward pp-amplitude changes from 0.14 at ISR-energies to 0.1 at 13 TeV. This decrease is sometimes interpreted as an indication on observation of Odderon—the C-odd analogue of Pomeron [26]. However there are some arguments [27] that the unitarity might be violated in this interpretation. Anyway, these values definitely show that the contribution of the real part of the amplitude to the differential cross section (quadratic in ρ) is at the level of about 1% inside the diffraction cone.

Thus, the three characteristics of soft interactions show some signs of changing the interaction mode at energies of about 10 GeV!

Probably, even more surprising and intriguing observation is recently done at larger transferred momenta. The preliminary TOTEM data at 13 TeV in Figure 5 show that the differential cross section decreases as a pure t-exponent for $0.7 < |t| < 3.5$ GeV^2. It tells us about a new substructure inside protons.

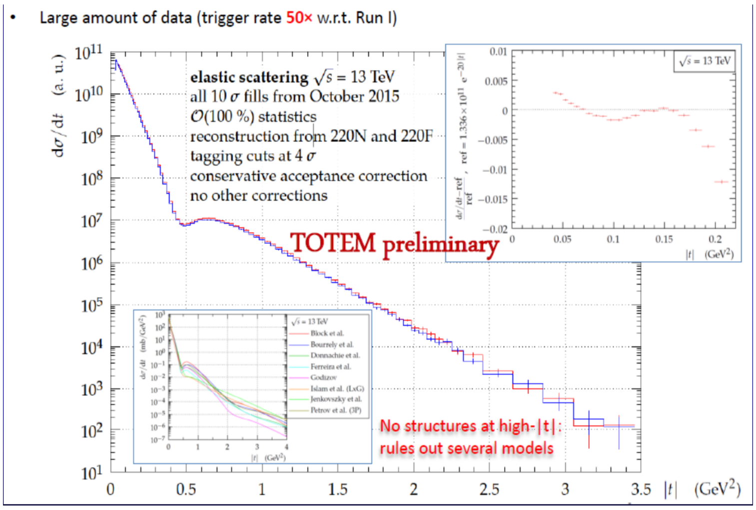

Figure 5. The differential cross section of elastic scattering of protons at 13 TeV [28].

The elastic scattering outside the diffraction cone was first measured at comparatively low energies. In 1964 it was found that the exponential decrease of the differential cross section typical for the diffraction cone slows down at larger transferred momenta somewhat and turns out to be of $\exp(-c\sqrt{|t|})$ shape [29]. It was named as Orear regime by the name of its discoverer. That could be explained in terms of the set of successive soft scatterings [30] and therefore did not ask for any special internal structure. More recent data at 7 TeV shown in Figure 3, right, became available in the comparatively small interval of transferred momenta up to 2.5 GeV^2. They are not precise enough to get the definite conclusions whether the same Orear regime holds and if any oscillations imposed on it are visible. In the recent data at 13 TeV (see the histogram in Figure 5) the range of measured transferred momenta has been extended up to 3.5 GeV^2. Surprisingly enough, they show the new regime of the exponential decrease with $|t|$ (but not with $\sqrt{|t|}$) and no oscillations. Their absence excludes the predictions of several phenomenological models shown by continuous lines in Figure 3, right. The exponent in this region is approximately six times smaller than B. It looks as if some harder central core appears inside protons. Analogously to the estimate of the proton external size by the value of $B \propto R^2$ one can evaluate the size of the internal coherence region from the slope at larger transferred momenta as being about 0.4 fm. Thus the new substructure of protons becomes visible at 13 TeV.

5. The Jets and the Ridge in Inelastic Processes

Many new characteristic features are observed in inelastic proton collisions as well. The jets and the ridge-effect are discussed at some length here. While jets can be described by a combination of the perturbative QCD regulations with some phenomenological input, there exist numerous proposals for explanations of the ridge so that further insight is asked for.

Jets are the narrow collimated groups of particles produced in high-energy collisions. They were first observed at Large Electron-Positron (LEP) collider. According to theoretical prescriptions, the annihilation of the high-energy pair of electron and positron can be described as the creation of the quark-antiquark pair with an intermediate stage of a virtual photon or a Z^0-boson. The two-jet events of the electron-positron annihilation were immediately interpreted as originating from hadronization of the produced quark-antiquark pair. No free quarks appeared. Once again it was demonstrated that the quarks carrying a color charge cannot exist in free state. Nevertheless, the angular distribution of jets keeps the memory about the direction of colliding partners. The process of color neutralization, which asks for some additional assumptions, does not spoil it completely. The deflection from this direction was predicted theoretically and confirmed by experiment. Measurements of three-jet production in electron-positron annihilation provided the first compelling evidence for the existence of gluons (gluon jets) in the final state. That gave us more confidence in existence of confined constituents which are cornerstones of QCD (see, e.g., [31]).

At high energies, protons are usually treated as bunches of point-like constituents—partons (quarks, gluons). The proton-proton collisions can be considered as a sequence of parton interactions. The large-angle scattering of two high-energy partons results in formation of oppositely moving jets which are registered in detectors as narrow collimated bundles of particles. By analysing energy and angular distributions of the jets experimentally, it is possible to reveal the properties of the basic constituents of matter, the parton content of hadrons and the nature of strong forces acting between them. The creation of jets can be treated perturbatively in QCD with account of multiparton interactions and usage of experimental information about the hadronization stage (see [32]). Thus experimental data can be confronted to theoretical predictions. In particular, a special approach to jet studies by analysing the extremely high-multiplicity events was attempted in [33]. It is interesting, because the properties of dense gluon configurations should become visible. The analysis showed a sizeble contribution from them to the number of produced jets. Usually the comparison is done with predictions of some Monte-Carlo models (see, e.g., [33]) and the preliminary results indicate that their refinement (in particular, for the denser gluon content of protons) is sometimes necessary to get a reasonable agreement.

High transverse momenta of jets allow to apply the general laws of perturbative QCD. In distinction to that, the phenomenon of the ridge-effect originates from the low-momentum particle correlations. It still asks for the theoretical interpretation.

The events of extremely high multiplicities surprised physicists with a peculiar effect known as ridge (see Figure 6). The correlations of two charged particles in such events were first studied in nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC). Later on, in studies of 4 collaborations at the LHC, it was shown that they have the similar shape in pp and p-Pb collisions. Correlation between the two particles is very wide in their rapidity difference $\Delta\eta$ and yet concentrated at small differences of their azimuthal angles $\Delta\phi$. Scaling is observed according to produced particle multiplicity rather than collision energy. Surely, this points to the universal origin due to the extremely high parton densities in these processes.

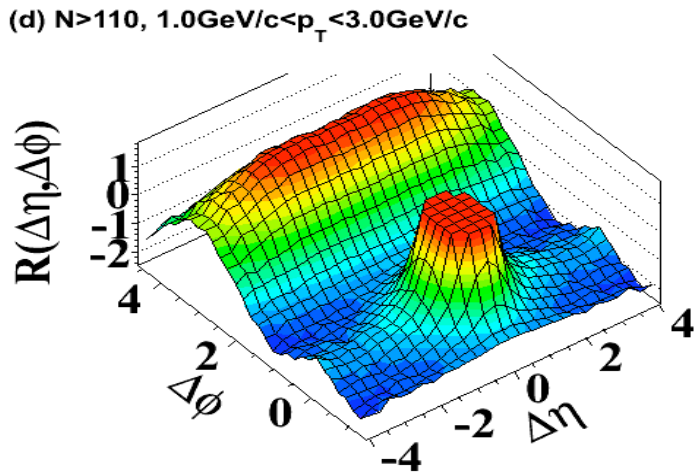

Figure 6. The peculiar ridge structure of correlations of particles created in inelastic collisions with high multiplicities (reproduced from CMS pp 7 TeV data [34]). Particles moving close to the detected particle form a peak with other accompanying particles forming a ridge along the beam ($\Delta\eta$) direction. Particles in the opposite azimuthal direction ($\Delta\phi = \pi$) populate a wide plateau.

If the first detected particle is energetic, it, most likely, is the leading particle in a jet and would then be surrounded by other particles. So there is a peak-like structure around the detected particle. This feature is clearly seen in Figure 6 (i.e., at $\Delta\phi, \Delta\eta = 0$). The balancing particles appear as an opposite side ridge plateau at $\Delta\phi \approx \pi$. The near side plateau at small $\Delta\phi$ looks as if the strings stretched between protons percolate [35] and break up into the oldfashioned clusters [36] moving fast along the string direction according to the multiperipheral kinematics [37]. Other interpretations of this effect have been proposed but no complete agreement is yet achieved.

6. Discussion

It is tempting to relate some of the above findings to the general shape and the new internal substructure of protons. Surely, the size of the interaction region of protons must increase with energy if their cross sections are increasing. The simplest picture of hadron interactions is that of two colliding quantum bags (pancakes after Lorentz transformation). The protons act as coherent entities at large distances. That is seen from the exponential behavior inside the elastic diffraction cone at small transferred momenta as well. The increasing height of the peak at very small transferred momenta and its width shrinkage fit reasonably well in the described picture. The shape of the interaction region can be obtained from the unitarity condition as reviewed, e.g., in [17]. Its evolution from ISR to LHC is shown in Figure 7. The darkness of inelastic processes $G(s,b) = d\sigma_{inel}/db^2$ increases. Surprisingly enough it shows complete attenuation $G = 1$ at LHC energies inside the region $b \leq 0.4$ fm for the most central collisions. Namely they should be responsible for larger transferred momenta of the elastic scattering as well. Therefore, the shape of the differential cross section outside the diffraction cone can be related a'la Rutherford to the existence of some new scale of about 0.4 fm inside protons. The coincidence of these two scales may be not accidental. These preliminary insights, got from the unitarity condition, help in the compilation of the spatial view but cannot replace the QCD treatment which is still missing.

Even more surprising is the increase of the survival probability of protons from ISR to LHC energies. It is hard to imagine that protons persist to stay intact stronger with increasing their collision energy. That problem is still waiting for the QCD explanation. Some more speculations in that respect can be found in [17].

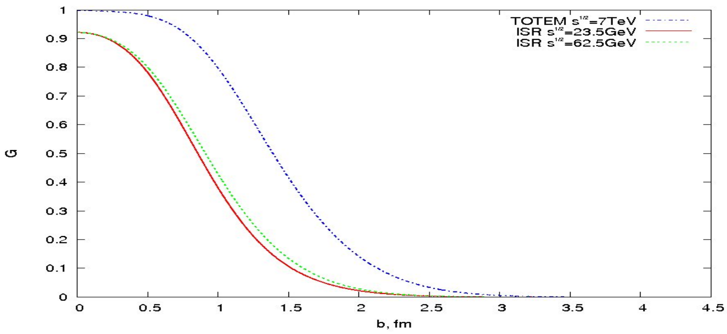

Figure 7. The overlap function $G(s, b)$ at 7 TeV (upper curve) [38] compared to those at ISR energies 23.5 GeV and 62.5 GeV (all of them are computed by using the fit of experimental data according to the phenomenological model [39]). The impact parameter, b, is defined as the transverse distance between the trajectories of the centers of the colliding protons.

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References

1. Rubbia, C. Experimental Observation of the Intermediate Vector Bosons W^+, W^- and Z^0. *Rev. Mod. Phys.* **1985**, *57*, 699–722. [CrossRef]
2. CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **2012**, *716*, 30–61.
3. ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC *Phys. Lett. B* **2012**, *716*, 1–29.
4. Druzhinin, P.A. Physics is supposed to be spoken of with a bit of irony—Unknown speech by L.D. Landau, 8 April 1960. *Phys.-Uspekhi* **2018**, *61*, 105. [CrossRef]
5. Denisov, S.P.; Donskov, S.V.; Gorin, Y.P.; Petrukhin, A.I.; Prokoshkin, Y.D.; Stoyanova, D.A.; Allaby, J.V.; Giacomelli, G. Total cross sections of π^+, K^+ and p on protons and deuterons in the momentum range 15–60 GeV/c. *Phys. Lett. B* **1971**, *36*, 415–421. [CrossRef]
6. Amaldi, U. Small-angle physics at the intersecting storage rings forty years later. *arXiv* **2012**, arXiv:1206.3954.
7. Amaldi, U.; Bryant, P.J.; Darriulat, P.; Hubner, K. 40th Anniversary of the First Proton-Proton Collisions in the CERN Intersecting Storage Rings (ISR). *arXiv* **2012**, arXiv:1206.4876.
8. Antchev, G.; Aspell, P.; Atanassov, I.; Avati, V.; Baechler, J.; Barrera, C.B.; Berardi, V.; Berretti, M.; Bossini, E.; Bottigli, U.; et al. First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies. *arXiv* **2017**, arXiv:1712.06153.
9. Froissart, M. Asymptotic Behavior and Subtractions in the Mandelstam Representation. *Phys. Rev.* **1961**, *123*, 1053–1057. [CrossRef]
10. Martin, A. Can one improve the Froissart bound? *arXiv* **2008**, arXiv:0812.0680.
11. Lipatov, L.N. Small-x physics in perturbative QCD. *Phys. Rep.* **1997**, *286*, 131–198. [CrossRef]
12. Ryskin, M.G.; Khoze, V.A.; Martin, A.D.; Shuvaev, A.G. Soft physics at the LHC. *J. Phys. G* **2009**, *36*, 093001. [CrossRef]
13. Dokshitzer, Y.L.; Khoze, V.A.; Söstrand, T. Rapidity gaps in Higgs production. *Phys. Lett. B* **1992**, *274*, 116–121. [CrossRef]
14. Bjorken, J.D. Rapidity gaps and jets as a new-physics signature in very-high-energy hadron-hadron collisions. *Phys. Rev. D* **1993**, *47*, 101–113. [CrossRef]
15. Gustafson, G. Minireview on diffraction. *EPJ Web Conf.* **2015**, *90*, 06002. [CrossRef]
16. McLerran, L. Strongly interacting matter at high energy density. *Int. J. Mod. Phys. A* **2010**, *25*, 5847–5864. [CrossRef]
17. Dremin, I.M. Some new discoveries at colliders. *Phys.-Uspekhi* **2018**, *188*, 437–445.

18. Rutherford, E. The Scattering of α and β Particles by Matter and the Structure of the Atom. *Philos. Mag.* **1911**, *21*, 669–688. [CrossRef]
19. Antchev, G.; Aspell, P.; Atanassov, I.; Avati, V.; Baechler, J.; Berardi, V.; Berretti, M.; Bossini, E.; Bozzo, M.; Brogi, P.; et al. First measurement of the total proton-proton cross section at the LHC energy of $\sqrt{s}$ = 7 TeV. *Europhys. Lett.* **2011**, *96*, 21002.
20. Antchev, G.; Aspell, P.; Atanassov, I.; Avati, V.; Baechler, J.; Berardi, V.; Berretti, M.; Bozzo, M.; Brücken, E.; Buzzo, A.; et al. Proton-proton elastic scattering at the LHC energy of $\sqrt{s}$ = 7 TeV. *Europhys. Lett.* **2011**, *95*, 41001.
21. Petrov, V.A.; Okorokov, V.A. The size seems to matter or where lies the "Asymptopia"? *Int. J. Mod. Phys. A* **2013**, *33*, 1850077. [CrossRef]
22. Khuri, N.N.; Kinoshita, T. Real part of the scattering amplitude and the behavior of the total cross-section at high energies. *Phys. Rev. B* **1965**, *137*, 720–729. [CrossRef]
23. Block, M.M.; Cahn, R. High-energy $p\bar{p}$ and pp forward elastic scattering and total cross sections. *Rev. Mod. Phys.* **1985**, *57*, 563–598. [CrossRef]
24. Dremin, I.M.; Nazirov, M.T. Real part of the forward elastic scattering amplitude and high-energy behavior of the total cross sections. *J. Exp. Theor. Phys. Lett.* **1983**, *37*, 163–166.
25. Antchev, G.; Aspell, P.; Atanassov, I.; Avati, V.; Baechler, J.; Barrera, C.B.; Berardi, V.; Berretti, M.; Bossini, E.; Bottigli, U.; et al. First Determination of the ρ-Parameter at $\sqrt{s}$ = 13 TeV—Probing the Existence of a Colourless Three-Gluon Bound State. CERN-EP-2017-335. Available online: http://cds.cern.ch/record/2298154 (accessed on 15 May 2018).
26. Martynov, E.; Nicolescu, B. Did TOTEM experiment discover the Odderon? *arXiv* **2017**, arXiv:1711.03288
27. Khoze, V.A.; Martin, A.D.; Ryskin, M.G. Black disk, maximal Odderon and unitarity. *Phys. Lett. B* **2018**, *780*, 352–356. [CrossRef]
28. Csörgö, T. Recent Results from TOTEM. In Proceedings of the Low-X 2017, Biscegli, Italy, 13–17 June 2017.
29. Orear, J. Transverse momentum distribution of protons in pp elastic scattering. *Phys. Rev. Lett.* **1964**, *12*, 112–113. [CrossRef]
30. Andreev, I.V.; Dremin, I.M. Elastic scattering at large angles. *J. Exp. Theor. Phys. Lett.* **1967**, *6*, 262.
31. Dremin, I.M.; Gary, J.W. Hadron Multiplicities. *Phys. Rep.* **2001**, *349*, 301–393. [CrossRef]
32. Snigirev, A.M. Possible indication to the QCD evolution of double parton distributions? *Phys. Rev. D* **2010**, *81*, 065014. [CrossRef]
33. Azarkin, M.Y.; Dremin, I.M.; Strikman, M. Jets in multiparticle production in and beyond geometry of proton-proton collisions at the LHC. *Phys. Lett. B* **2014**, *735*, 244–249. [CrossRef]
34. Khachatryan, V.; CMS Collaboration. Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC. *J. High Energy Phys.* **2010**, *2010*, 91. [CrossRef]
35. Andres, C.; Moscoso, A.; Pajares, C. The onset on the ridge structure in AA, pA and pp collisions. *Nucl. Part. Phys. Proc.* **2016**, *273*, 1513–1518. [CrossRef]
36. Dremin, I.M.; Quigg, G. The cluster concept in multiple hadron production. *Science* **1978**, *199*, 937–941. [CrossRef] [PubMed]
37. Dremin, I.M.; Kim, V.T. Towards a common origin of the elliptic flow, ridge and alignment. *J. Exp. Theor. Phys. Lett.* **2010**, *92*, 652–653. [CrossRef]
38. Dremin, I.M.; Nechitailo V.A. Proton periphery activated by multiparticle dynamics. *Nucl. Phys. A* **2013**, *916*, 241–248. [CrossRef]
39. Amaldi, U.; Schubert, K.R. Impact parameter interpretation of proton-proton scattering from a critical review of all ISR data. *Nucl. Phys. B* **1980**, *166*, 301–320. [CrossRef]