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Some new discoveries at colliders

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Contents

Abstract. Five of the most recent experimental discoveries about high-energy proton interactions are chosen to demonstrate the predictive power of the existing theory and its striving to elucidate the origin of some less understood phenomena. These include the Higgs boson, the cross section increase with energy, an increased fraction of elastic scattering in the same energy range, the exponential fall-off of the elastic differential cross section at sufficiently large momentum transfers (small distances), and the jet emission and ridge formation phenomena observed in very-high-multiplicity inelastic processes.

Keywords: proton, elastic scattering, unitarity condition

The latest advances in physics are based on the previous ones, and the previous ones on the ones before, and so on.[1]
L D Landau

1. Introduction

The continuity of the progress in physics is based on a chain of discoveries. High-energy particle physics started from studies of cosmic rays, which revealed many unexpected features of particle interactions. The construction of particle accelerators and, later on, colliders helped greatly improve the quality of the experimental data concerning particle properties. Currently, the most impressive results are coming from the Large Hadron Collider (LHC). Proton beams collide there with an energy up to 13 TeV in their center-of-mass system (c.m.s.) ($\sqrt{s} \leqslant 13$ TeV), exceeding their own rest mass by more than 4 orders of magnitude. The main goal of studies at the LHC is to understand the forces governing particle interactions and the internal structure of the fundamental blocks of matter.[2]

The theory of such forces is now known as the Standard Model, which unifies strong and electroweak interactions. Although there are currently no indications of critical deviations from its predictions, they are actively being sought in experimental data and different theoretical possibilities of modifying the model are being discussed. These are grounded in new experimental and observational facts requiring their description and understanding, as well as in some original theoretical hypotheses. We just mention questions such as dark matter and dark energy, and the search for supersymmetric partners of observable particles. At the same time, not all experimental facts can find an explanation, maybe just due to our inability to develop some new methods of calculations in the Standard Model framework. This problem is especially clearly seen in the case of strong interactions with the large coupling constant (so-called 'soft' hadron collisions). Some of them are discussed in this paper.

We first briefly describe the discovery of the Higgs boson at the LHC and then address some new features of proton interactions that require further interpretation and deeper understanding. Then we speculate on possible implications and explanations of the observed phenomena in the hope of motivating the reader to propose new ones.

One of the first surprising observations in the 1950s studies of high-energy particle interactions was the phenomenon of resonances, seen as some peaks in the relatively monotonic behavior of their interaction cross sections. Interpreted in terms of the quantum levels of an interacting system, they were identified as newly produced unstable particles. It turned out that the number of resonances with

[1] From a talk given by Landau in 1960, reconstructed from a tape recording and published in [1].

[2] We 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.

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different quantum characteristics is so numerous that the special tables of them are published by the Particle Data Group (PDG). Parallel to experimental findings, the theory of particle interactions was being developed very successfully. The resonances were classified and their internal structure was described by the Standard Model. Nevertheless, some crucial elements of the scheme were still missing. The short range of electroweak forces became understood after the observation in 1983 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. Their connection with the final piece of the Standard Model, the Higgs boson, was evident.

However, it took almost 30 years to proceed to higher energies for the LHC in search for heavier resonances. Even though some quantum characteristics of the new boson were predicted by the Standard Model, nobody was absolutely sure about the success of this search, because the boson mass was not fixed. Some theoretical predictions based on general theory principles made as early as 1964 [2–4] supported enthusiasts. Finally, the decisive element of the Standard Model (in its minimal modification scheme) was found in 2012 as a resonance in the search for some definite channels of its decay [5, 6]; this was the Higgs boson, with a mass of about 125 GeV. It is a great common success of both theory and experiment. It validates the Standard Model and shows that we are on the right path to understanding the cornerstone problem of the origin of masses of some fundamental particles and constituents of matter. The Higgs boson is a scalar particle, as opposed to all other vector bosons transmitting interactions — photons, gluons, and $W^{\pm}$ and Z^0 bosons. The Higgs field is thought to fill the entire universe. The authors of the theoretical prediction [1, 2] were awarded the Nobel prize in physics in 2013.

It is a relatively rare situation in physics when theoretical predictions come earlier than their experimental verification and wait for about 50 years to be awarded a Nobel prize. It happens more often that experimental findings wait for their theoretical treatment. The best example is provided by the history of superconductivity. This phenomenon was first observed in 1911 and was explained in 1957, almost 50 years later. We quote Landau once again: "The knowledge of the general laws of physics does not necessarily imply the understanding of a particular phenomenon" [1].

Just such 'particular' phenomena are described and discussed below. They are difficult to interpret because the observed effects lie in the domain of the strong interaction forces and should be explained by Quantum Chromodynamics (QCD). The most widely used theoretical method in physics is the perturbative approach with its power-series expansion relying on the smallness of the coupling constant. However, it can be applied in QCD only for rather rare collisions with large transferred momenta (or masses), where the coupling strength becomes small due to the asymptotic freedom property, unique to QCD. It does not work for the main bulk of 'soft' hadron interactions with low transferred momenta, where the coupling constant is quite large. Phenomenological models are mostly used to describe experimental characteristics there. Usually, many adjustable parameters are introduced in these models, making their predictions very flexible and less definite. Some (rather limited) help can be received from the general principles of analyticity and unitarity of the scattering amplitudes. We now pass to a description of the above-mentioned phenomena. First, we briefly present experimental results, and then discuss them and try to explain some of them.

2. Energy dependence of the interaction cross sections

Physics results obtained at fixed-target accelerators dominated until the 1970s. The proton–proton total cross section steadily decreased with the energy increase. Theorists believed that it would decrease further, somewhat similarly to the cross section of electron–positron annihilation or, at best, tend asymptotically to a constant value related to the proton size of the order of 1 fm. This belief was first strongly challenged in 1971 [7] by measurements at the Serpukhov accelerator (with the available c.m.s. energy $\sqrt{s}$ of about 12 GeV). The measured cross section of the interaction of positively charged kaons (K^+) with protons started to increase slightly at energies from 8 to 12 GeV. At the very beginning, this effect was not taken sufficiently seriously. However, it soon became well recognized in proton–proton collisions after being confirmed by the increase in their total cross section at the Intersecting Storage Rings (ISR) collider by about 10% in the wider energy range from about 10 to 62.5 GeV [8]. Currently, a much stronger effect is clearly seen at the LHC up to 13 TeV, as is demonstrated in Fig. 1 for the total, inelastic, and elastic cross sections. The total cross section increases by more than 2.5 times from the ISR (E_{IRS}) to LHC (E_{LHC})! Cosmic ray data are obtained by two collaborations, Auger and Telescope Array. They also support this tendency to higher energies of almost 100 TeV, albeit with a much lower precision. Some of the data are also shown in Fig. 1.

Such a behavior tells us that the size of the interaction region of protons becomes larger at higher energies. An upper bound on the increase in 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 (the 'Froissart–Martin bound'). However, the coefficient of the logarithm is so large that phenomenologically, at present energies, it does not rule out the use of a slow power-law energy dependence. The increase in hadronic cross sections is understood within scattering theory as being due to a virtual exchange of vacuum quantum numbers, known within Regge theory as a Pomeron. The power-like dependence can be ascribed to the exchange of the so-called 'supercritical Pomeron', i.e., a pole singularity with the intercept exceeding 1. The very existence of such a Pomeron or other suitable Reggeon singularity, as well as their dynamical origin, is still unclear.

3. Energy dependence of the elastic-to-total cross section ratio

If the behavior of the total cross section can be phenomenologically interpreted in terms of Reggeon exchanges, a yet unsolved puzzle is provided by the energy dependence of the ratio of the elastic cross section to the total cross section. It is shown in Fig. 2 that this ratio also increases from the ISR to LHC by more than 1.5 times. Probably, a more impressive way to express this is by comparing inelastic and elastic cross sections. The inelastic cross section is about 5 times larger than the elastic one at the ISR, while their ratio is less than 3 at the LHC energies.

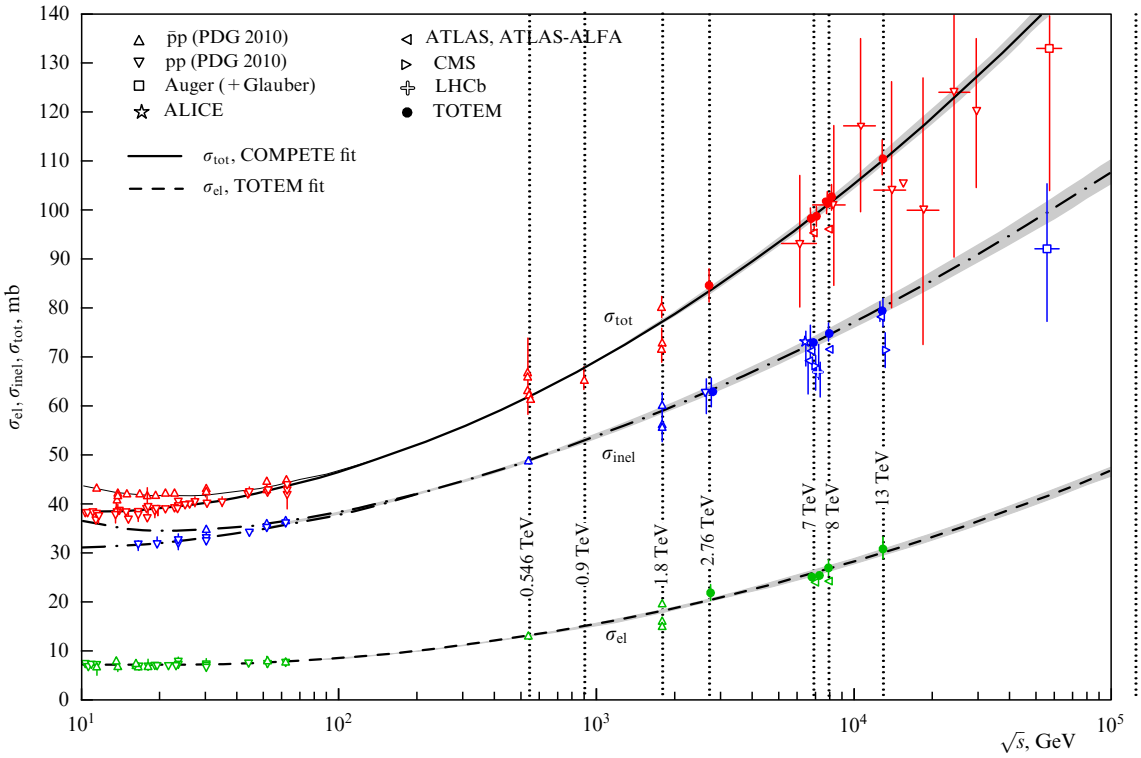

Figure 1. (Color online.) Energy dependence of the total, elastic, and inelastic proton–proton cross sections [9]. ALICE — A Large Ion Collider Experiment, ATLAS — A Toroidal LHC ApparatuS, ALFA — Absolute Luminosity For ATLAS, CMS — Compact Muon Solenoid, LHCb — Large Hadron Collider beauty, TOTEM — TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC.

The ordinate axis in Fig. 2 tells us that the survival probability of protons leaving the interaction region intact is high enough and, what is more surprising, increases at higher energies. In other words, even though the protons are hit more strongly, they do not break up, producing secondary particles in inelastic collisions but trying to keep their integrity. That contradicts our intuition based on classical prejudices. Naively, one could imagine the protons as two Lorentz-compressed bags colliding at 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 — as free states. Hence, these constituents can be created only in colorless combinations manifested in inelastic collisions as newly produced ordinary particles and resonances. The dynamics of internal fields during collisions and color neutralization is still unclear. However, just this dynamics must be responsible for the observed increase in the proton survival probability.

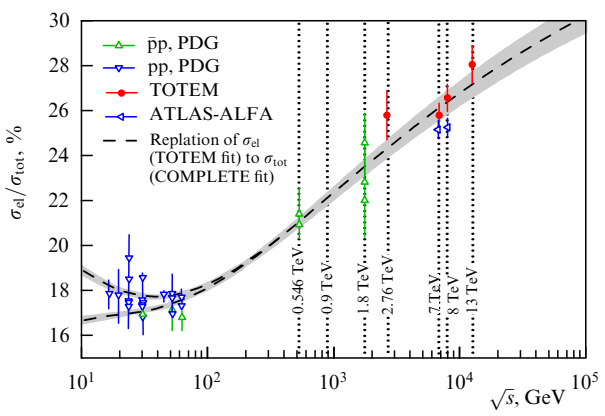

Figure 2. (Color online.) Energy dependence of the ratio of the elastic to total proton–proton cross sections (survival probability) [9].

We could imagine the classical analogy to the bag model as a Kinder-Surprise toy with many unseen pieces hidden inside it. They appear outside if two such toys are broken in a collision. These toys never stay intact if hit strongly enough. Hence, the increase in the survival probability of protons upon increasing their collision energy is a purely quantum effect.

4. Differential cross section of elastic scattering

Some interesting observations were made very recently in measuring the shapes of differential cross sections of elastic scattering at both small and relatively large transferred momenta.

The dependence of the elastic differential cross section on the transferred momentum is also important for understanding the global features of the internal structure of protons. For small angular deflections, the momentum transfer can be low enough, such that the wave description becomes appropriate. The corresponding wavelength (inversely proportional to the momentum transfer) is comparable to the dimensions of the proton, and the resulting diffraction pattern (the angular distribution) reveals this dimension. 'Hard scattering' (i.e., large momentum transfer) implies a more localized scattering center (as first pointed out by Rutherford).

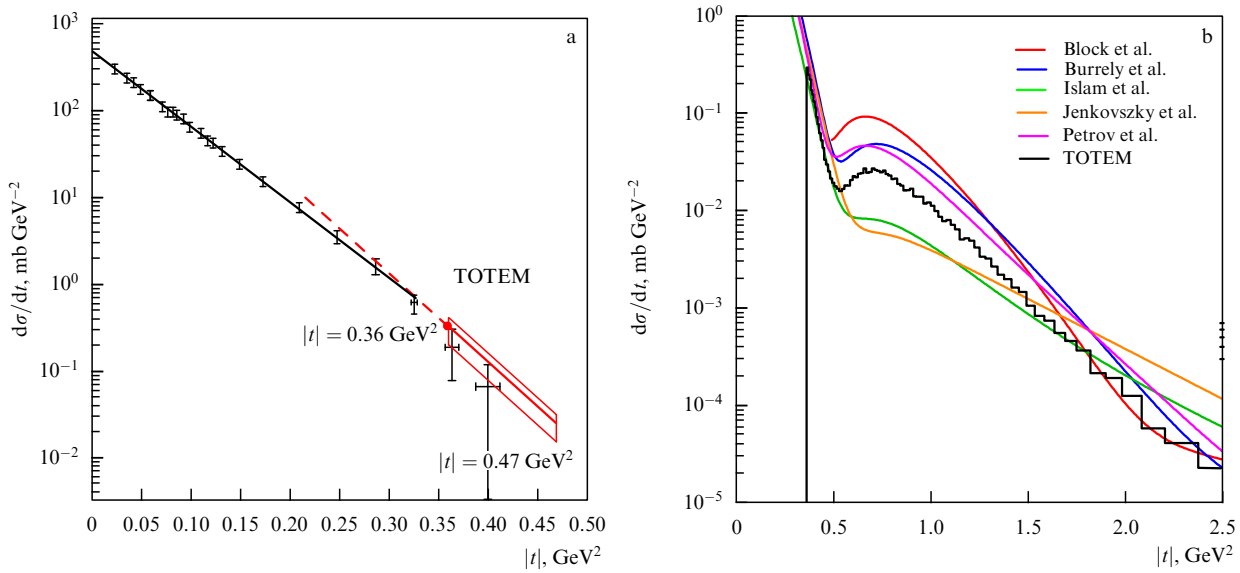

Figure 3. (Color online.) Differential cross section of elastic proton–proton scattering at the energy $\sqrt{s} = 7$ TeV measured by the TOTEM collaboration. (a) The region of the diffraction cone with the $|t|$-exponential decrease [10]. (b) The region outside the diffraction peak [11]. The predictions of five models are demonstrated.

At small scattering angles θ, the shape of the differential cross section $d\sigma/dt$ can be approximately described by a Gaussian exponential (see Fig. 3). It is described quite well by various phenomenological models, in particular, by those using the Reggeon approach. The slope B of the diffraction peak $d\sigma/dt \propto \exp(Bt)$ (where $-t = 2p^2(1-\cos\theta) \approx p^2\theta^2$, with p being 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 Fig. 1, and its width shrinks such that the slope becomes steeper at higher energies. According to the Reggeon approach, the slope B should increase with the energy logarithmically, $B \propto \ln s$. The energy dependence measured in experiment is shown in Fig. 4. Surprisingly enough, it looks as if the rate of this growth also increases, violating the simple Reggeon pole prescriptions as seen from the LHC data. The cone height at forward scattering grows as $\ln^2 s$, while its width shrinks as $\ln^{-2} s$. The typical size of the hadron interaction region, still being about 1 fm in size, grows with the energy increase.

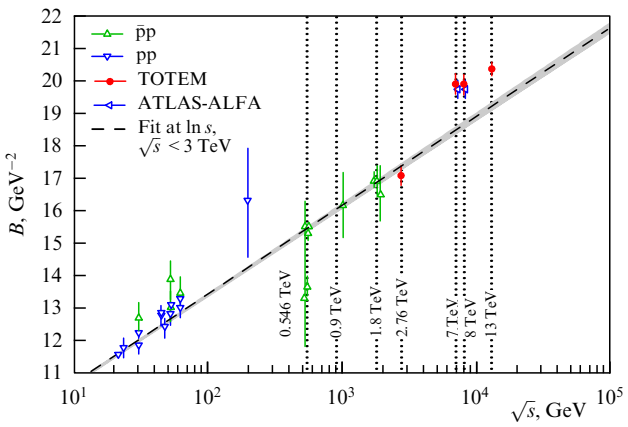

Figure 4. Energy dependence of the slope B of the diffraction cone [9].

We mention an intriguing correlation between the energy dependences of the total cross section and of the diffraction cone slope at somewhat lower energies. Both of them drastically change their behavior at energies of about 10 GeV. The total cross section passes a minimum there and starts increasing, as shown in Fig. 1. The slope changes its fast (almost linear) increase with energy to a much slower (logarithmic?) dependence, shown in Fig. 4. The relation of this correlation to the spatial picture of proton interaction is discussed in [12].

It is interesting that the real part of the forward elastic scattering amplitude changes its sign from negative to positive just at the same energies; this has been shown from measurements of the interference between the nuclear and Coulomb contributions to the differential cross section. The dispersion relations, expressing the real part as an integral of the forward imaginary part (i.e., of the total cross section, according to the optical theorem), predicted this effect even earlier.

Probably, more surprising and interesting are the recent results of measurements of the elastic differential cross section at 13 TeV with relatively large transferred momenta.

As regards elastic scattering at larger angles, it was first measured at relatively low energies. In 1967, it was found that the exponential decrease in the differential cross section typical for the diffraction cone slows down somewhat at larger transferred momenta and turns out to have the shape $\exp(-c\sqrt{|t|})$, named the Orear regime for the name of its discoverer. It could be explained in terms of a sequence of soft scatterings, and it did not therefore require any special internal structure. More recent data at 7 TeV shown in Fig. 3 (the right histogram) became available in the relatively small interval of transferred momenta up to 2.5 GeV^2. They are not precise enough to reach definitive conclusions on whether the same Orear regime holds and whether any oscillations imposed on it are visible, as predicted by several phenomen-

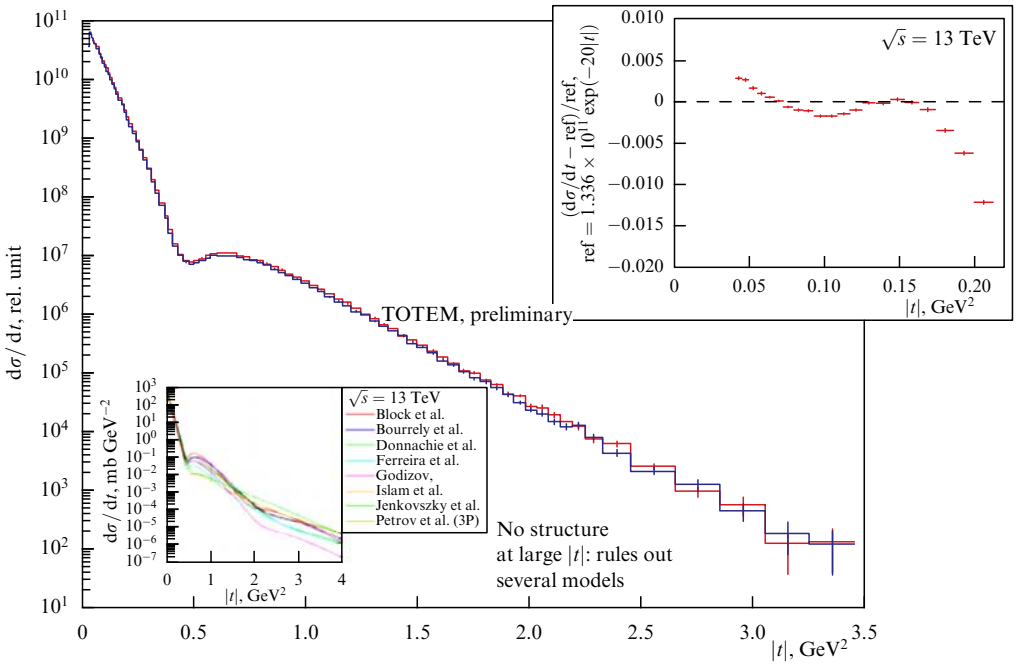

Figure 5. (Color online.) Differential cross section of elastic scattering of protons at 13 TeV [13]. The upper inset shows the structure inside the diffraction cone, the lower inset shows predictions of eight theoretical models at 13 TeV.

ological models (see Fig. 3b). In recent preliminary data at 13 TeV (see Fig. 5), the range of measured transferred momenta was extended to 3.5 GeV^2 [3]. Surprisingly enough, they show the new regime of the exponential decrease with $|t|$ (but not with $\sqrt{|t|}$!) and no oscillations. The exponential in this region is much smaller than B and shows the size of the coherence region to be about 0.4 fm. Thus, the new substructure of protons becomes visible at 13 TeV!

5. Jets and the ridge in inelastic processes

Many new characteristic features are also observed in inelastic proton collisions. Here, we mention and discuss two of them: jets and the ridge.

Jets are narrow collimated groups of particles produced in high-energy collisions. They were clearly observed at the LHC. Earlier, their creation was studied at the Large Electron–Positron collider (LEP). According to theoretical prescriptions, the annihilation of a high-energy electron–positron pair must lead to the creation of a quark–antiquark pair. The observed two-jet events of the electron–positron annihilation were immediately interpreted as originating from hadronization of the produced quark–antiquark pair. Once again, it was demonstrated that quarks carrying a color charge cannot exist in free form. Nevertheless, they keep the memory about the direction of colliding partners, which was not obliterated by the process of color neutralization. The deflection from this direction was predicted theoretically and confirmed experimentally. Measurements of three-jet production in annihilation provided the first compelling evidence for the existence of gluons in the final state. That gave us more confidence in the 'existence' of 'invisible' confined constituents.

At high energies, protons are usually treated as bunches of point-like constituents — partons (quarks, gluons). Proton–proton collisions can be regarded as a sequence of parton interactions. The large-angle scattering of two high-energy partons results in the formation of oppositely moving jets, which are registered in detectors as narrow collimated bundles of particles. Analyzing energy and angular distributions of the jets experimentally allows revealing 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 multiparton interactions taken into account. Thus, experimental data can be compared with theoretical predictions. Experimental data about jets are so numerous that it is impossible to show them here. We only mention a special approach to jet studies by analyzing extremely high-multiplicity events. This is interesting because the specific properties of dense gluon configurations should become visible just there. Usually, the comparison is done with predictions of some Monte Carlo models, and the preliminary results indicate that their refinement (for example, for the denser gluon content of protons) is sometimes needed in order to obtain a reasonable agreement.

Events with extremely high multiplicities surprised physicists by a peculiar effect known as the ridge (Fig. 6). The correlations of two charged particles in such events were first studied in nucleus–nucleus collisions at the Relativistic Heavy Ion Collider (RHIC). At the LHC, it was recently shown that they have a similar shape in pp and p–Pb collisions. A correlation between particles is very wide in the rapidity difference $\Delta\eta$ and yet concentrated at small azimuthal angles $\Delta\phi$. Scaling is observed according to the

[3] Recently, new data in the range up to 3.8 GeV^2 were presented in the talks by F Ravera on behalf of the TOTEM collaboration (the 134th LHCC meeting, open session 30 May 2018) and F Nemes on behalf of the TOTEM collaboration (in the proceedings of the 4th Elba workshop on Forward Physics at LHC energy, 24–26 May 2018, to be published in a special issue of *Instruments*).

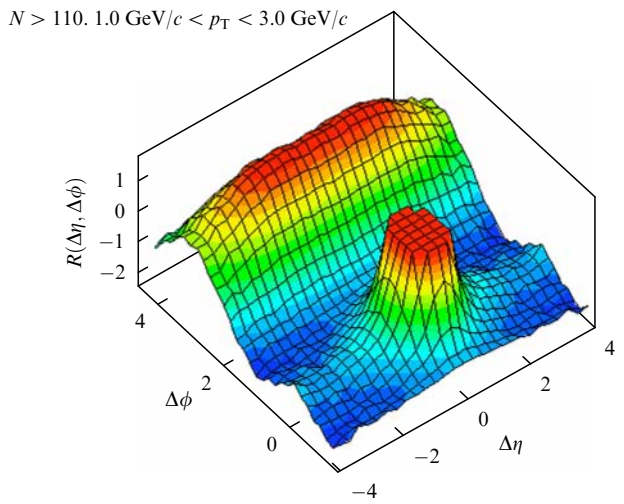

Figure 6. Peculiar 'ridge' structure of correlations of particles created in inelastic collisions with high multiplicities, as reported by the CMS experiment at the LHC. Particles moving close to the detected particle form a peak, with other accompanying particles forming a 'ridge' along the beam ($\Delta\eta$) direction. Particles in the opposite azimuthal direction ($\Delta\phi = \pi$) populate a wide plateau.

produced particle multiplicity rather than the collision energy. Surely, this points to a universal origin due to the extremely high parton densities in these processes and probably to the formation of the quark–gluon plasma, where quarks and gluons become deconfined.

If the first detected particle is energetic, it is most likely the leading particle in a jet, and would then be surrounded by other particles. Therefore, there is a peak-like structure around the detected particle. This feature is clearly seen in Fig. 6 (i.e., at $\Delta\phi$, $\Delta\eta = 0$). The particles preserving the momentum balance form a 'ridge' plateau on the opposite azimuthal side $\Delta\phi \approx \pi$. The 'near side' plateau looks as if the strings stretched between protons break up into old-fashioned clusters moving fast along the string direction. Other interpretations of this effect have been proposed, but no complete agreement has yet been achieved.

6. Discussion and conclusions

It is tempting to relate some of the above findings to the general shape and 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 bags (pancakes after a Lorentz transformation). The protons act as coherent entities at large transverse distances. That can also be seen from the exponential behavior inside the elastic diffraction cone at small transferred momenta. The increase in the cross section at very small transferred momenta and its width shrinkage fit reasonably well in the described picture.

More surprising is the increase (at higher energies) of the survival probability of protons and the exponential regime of the elastic differential cross section at larger transferred momenta, which can be explained in the manner of Rutherford as the existence of some new scale inside protons. The successive elastic scatterings at small angles should lead to its less acute decrease than the exponential one observed at 13 TeV. That can be demonstrated by using the unitarity condition for the elastic amplitude A in the form

$$\operatorname{Im} A(p,\theta) = I_2(p,\theta) + g(p,\theta) = \frac{1}{32\pi^2}\iint \mathrm{d}\theta_1\,\mathrm{d}\theta_2 \times \frac{\sin\theta_1 \sin\theta_2 A(p,\theta_1)\,A^*(p,\theta_2)}{\sqrt{\left[\cos\theta - \cos(\theta_1+\theta_2)\right]\left[\cos(\theta_1-\theta_2) - \cos\theta\right]}} + g(p,\theta). \tag{1}$$

The integration region in (1) is defined by the conditions

$$|\theta_1 - \theta_2| \leqslant \theta\,, \qquad \theta \leqslant \theta_1 + \theta_2 \leqslant 2\pi - \theta\,. \tag{2}$$

The integral term represents the elastic two-particle intermediate states (the same as the incoming particles). The function $g(p,\theta)$ describes the shadowing contribution of the inelastic processes to the elastic scattering amplitude. The successive elastic scatterings of protons would correspond to iterative contributions to the term I_2 of the diffraction cone behavior of the amplitude A. Each iterative step with a Gaussian dependence on the angle produces a wider (twofold, threefold, etc.) contribution. Their sum reproduces the Orear-like shape. It was shown in [14] to arise from the solution of the corresponding linear integral equation. Therefore, the steeper exponential behavior must be a signature of interference somewhat compensating elastic intermediate steps in I_2 by the inelastic overlap term g, demonstrating the coherent influence of the subregion 0.4 fm in size on proton scattering.

A similar subregion appears directly in studies of the inelastic overlap contribution at the LHC energies in terms of impact parameters. The impact parameter b is defined as the transverse distance between the trajectories of the centers of colliding protons. Although it is not measurable directly in experiment, it probes the spatial region of the interaction. Applying the Fourier–Bessel transform to Eqn (1), we obtain the unitarity condition in the b-representation

$$G(s,b) = 2\operatorname{Re}\Gamma(s,b) - \left|\Gamma(s,b)\right|^2, \tag{3}$$

where

$$\mathrm{i}\Gamma(s,b) = \frac{1}{2\sqrt{\pi}}\int_0^\infty \mathrm{d}|t|\,A(s,t)\,J_0\left(b\sqrt{|t|}\right). \tag{4}$$

The overlap function G (in the b-representation) in Eqn (3) describes the transverse impact-parameter profile of inelastic collisions of protons, i.e., their probability distribution as a function of the impact parameter. This is just the Fourier–Bessel transform of the overlap function g, and it satisfies the inequalities $0 \leqslant G(s,b) \leqslant 1$ and determines how absorptive the interaction region is depending on the impact parameter (with $G = 1$ for full absorption and $G = 0$ for complete transparency). The profile of elastic processes is determined by the subtrahend in Eqn (3). Integrating $G(s,b)$ over the impact parameter leads to the cross section of inelastic processes. The terms in the right-hand side would produce the total cross section and the elastic cross section.

The right-hand side of Eqn (3) contains the elastic amplitude only and can be computed if known experimental data are inserted in it. This has been done for both ISR and LHC energies, with the results shown in Fig. 7. It shows that the darkness of protons increases from the ISR (lower curves [15]) to LHC energies [16], and their size also increases. Thus, protons become blacker, edgier, and larger (the BEL regime).

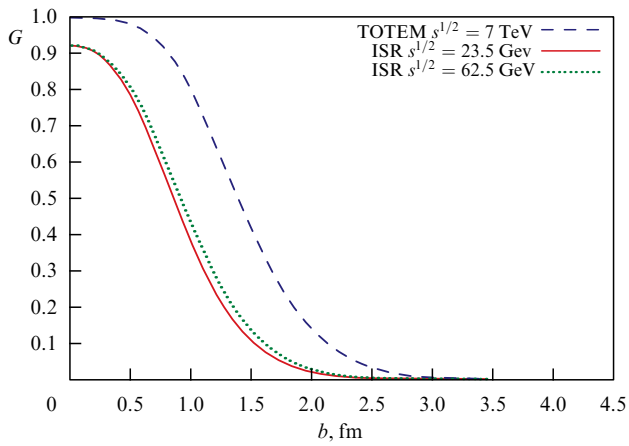

Figure 7. Overlap function $G(s, b)$ at 7 TeV (upper curve) [16] compared to those at ISR energies 23.5 GeV and 62.5 GeV (all of them are computed by using the fit of experimental data according to the phenomenological model [15]).

We note that the inelastic profile at the LHC develops a dark plateau about 0.4 fm in size, similar to the estimates of the extension of the subregion from elastic scattering at large transferred momenta. This is a completely dark region of central collisions. Nevertheless, the inelastic cross section of such collisions is rather small because of the smallness of the integration range over impact parameters. Its estimate corresponds well to the cross section of events with very high multiplicity (see [17]), where jets and the ridge were observed. Hence, we can surmise that this central region can be densely populated by gluons. Its evolution at higher energies is widely debated. There are models [18, 19] that predict that the profile stays saturated at the center with slight widening, but there are some arguments that this BEL shape might transform into a toroid-like one [20–23].

The origin of the increase in the survival probability is still not clear. Without a doubt, the strongest correlations and the collective behavior of the constituents must be responsible for this effect. In particular, the stronger role of elastic scattering might be explained if we assume that the shell of the bag strengthens at higher energies. In other words, this effect could be ascribed to the strengthening of strings connecting the quarks inside protons under the Lorentz contraction of the bags. The emission of soft gluons (the inelastic channel) would become less probable. This should spur further QCD studies of the energy dependence of confinement forces.

Another possible explanation of the increasing survival probability can be related to the fact that the density of extremely soft (wee) gluons inside protons would increase with increasing energy. There are some arguments that the strength of their interaction becomes smaller at such densities, i.e., that the coupling of super-soft infrared gluons is small [24]. In QCD, this effect can be related to a special topological structure of the QCD vacuum and the appearance of the so-called contact θ-term in the QCD Lagrangian [25]. Up to now, we knew only about the smallness of the coupling constant for hard collisions (asymptotic freedom). The high pressure during proton collisions and the extremely high density of soft gluons could result in a lower coupling strength and gluon condensation, which would depend on energy [26].

Coherent effects due to Bose–Einstein condensates are well studied in superfluidity, superconductivity, and laser physics. Color flux tubes are similar to vortex lines in superfluidity and superconductivity [27]. The overpopulated 'superfluid' component of the gluon field might form inside protons. It is less active in inelastic collisions. That would allow protons to 'penetrate' one another more easily, maintaining their integrity. We can try to ascribe these properties to topological gluon field configurations (called baryon junctions), which would have the superconducting properties of fullerenes [28]. Inside protons, a Y-shaped string network has a junction at the Fermat point of the triangle of quarks positioned at its vertices. Junction properties can be described by a five-dimensional string model in a curved space [29]. It would be a surprise to find that the size of such a junction is about 0.4 fm! However, it still remains in the realm of fiction. The coupling of that scale to the typical hadron size can probably also explain some regularities in the transverse momentum distributions. The long-distance physics of the confining force would saturate the increase in the survival probability within unitarity limits. That is just one of several possible speculative hypotheses proposed to account for this effect, paving the way towards its complete description.

To conclude, the unexpected (and as yet unexplained!) increase in the survival probability of protons from E_{IRS} to E_{LHC} is the most puzzling effect among other features of proton interactions described above. Surely, all of them are related to the energy evolution of the spatial profile of protons. The profile becomes blacker, edgier, and larger at present energies. Its fate at higher energies is determined by the energy behavior of the integral of the imaginary part of the elastic scattering amplitude over all transferred momenta, which cannot be extracted from only experimental data and has to be treated in the framework of some phenomenological models. Nevertheless, precise experimental measurements of the elastic cross section of colliding protons at higher energies will provide us with some guidelines as to the further evolution of the structure of their interaction region. In particular, we may see whether the second spatial scale shows its signature and whether protons continue to be black at still higher energies, or rather become somewhat gray. The novel many-body QCD regime of gluon saturation may help in describing the above effects and lead to new results for inelastic processes as well. At a deeper level, we can learn about the structure of the QCD vacuum that is responsible for the strongest force of nature.

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References

1. Druzhinin P A *Phys. Usp.* **61** 105 (2018); *Usp. Fiz. Nauk* **188** 113 (2018)
2. Higgs P W *Phys. Lett. B* **12** 132 (1964)
3. Englert F, Brout R *Phys. Rev. Lett.* **13** 321 (1964)
4. Guralnik G S, Hagen C R, Kibble T W B *Phys. Rev. Lett.* **13** 585 (1964)
5. Chatrchyan S et al. (CMS Collab.) *Phys. Lett. B* **716** 30 (2012); arXiv:1207.7235
6. Aad G et al. (ATLAS Collab.) *Phys. Lett. B* **716** 1 (2012); arXiv:1207.7214
7. Denisov S P et al. *Phys. Lett. B* **36** 415 (1971)
8. Amaldi U, in *40th Anniversary of the First Proton-Proton Collisions in the CERN Intersecting Storage Rings (ISR), Colloquium, 18 January 2011, CERN, Geneva, Switzerland* (CERN-2012-004) (Geneva: CERN, 2012) p. 33; arXiv:1206.3954; Amaldi U et al. *40th Anniversary of the First Proton-Proton Collisions in the CERN*

Intersecting Storage Rings (*ISR*), *Colloquium, 18 January 2011, CERN, Geneva, Switzerland* (CERN-2012-004) (Geneva: CERN, 2012); arXiv:1206.4876
9. Antchev G et al. (TOTEM Collab.), arXiv:1712.06153
10. Antchev G et al. (TOTEM Collab.) *Nucl. Phys. B* **899** 527 (2015)
11. Antchev G et al. (TOTEM Collab.) *Phys. Rev. Lett.* **111** 012001 (2013)
12. Petrov V A, Okorokov V A, arXiv:1802.01559
13. Csörgö T, talk at *Low x 2017, 12 – 18 June 2017, Biscegli*
14. Andreev I V, Dremin I M *JETP Lett.* **6** 262 (1967); *Pis'ma Zh. Eksp. Teor. Fiz.* **6** 810 (1967)
15. Amaldi U, Schubert K R *Nucl. Phys. B* **166** 301 (1980)
16. Dremin I M, Nechitailo V A *Nucl. Phys. A* **916** 241 (2013)
17. Azarkin M Yu, Dremin I M, Strikman M *Phys. Lett. B* **735** 244 (2014)
18. Kohara A K, Ferreira E, Kodama T *Eur. Phys. J. C* **74** 3175 (2014)
19. Petrov V A, Samokhin A P, in *XXXIth Intern. Workshop on High Energy Physics Critical Points in the Modern Particle Physics, July 5 – 7, 2017, Protvino, Moscow Region, Russia*; arXiv:1801.03809
20. Dremin I M *Phys. Usp.* **60** 333 (2017); *Usp. Fiz. Nauk* **187** 353 (2017)
21. Albacete J L, Soto-Ontoso A *Phys. Lett. B* **770** 149 (2017)
22. Arriola E R, Broniowski W *Phys. Rev. D* **95** 074030 (2017)
23. Dremin I M, Nechitailo V A, White S N *Eur. Phys. J. C* **77** 910 (2017)
24. Blaizot J-P et al. *Nucl. Phys. A* **904 – 905** 829c (2013); arXiv:1210.6838
25. Kharzeev D E, Levin E M *Phys. Rev. Lett.* **114** 242001 (2015)
26. Blaizot J-P, Liao J *Nucl. Phys. A* **949** 35 (2016); arXiv:1503.07263
27. Zhitnitsky A *Nucl. Phys. B* **916** 510 (2017); arXiv:1609.08619
28. Csörgö T, Gyulassy M, Kharzeev D *J. Phys. G* **30** L17 (2004)
29. Andreev O *Phys. Rev. D* **93** 105014 (2016)