A journey to understand the proton

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Abstract

After an introduction about the Large Hadron Collider at CERN, Geneva, Switzerland, we discuss briefly the proton structure in terms of quarks and gluons and stress the kinematical domain of high gluon density at the LHC. We also present diffractive and photon-induced events when protons are intact after interaction that are sensitive to beyond standard model physics with unprecedented precision, for instance the production of axion-like particles. Elastic events also led to the discovery of the odderon, This talk was presented as a general public talk for high school students during the ISMD 2023 workshop, Gyöngyös, Hungary.

1 Introduction: The Large Hadron Collider at CERN

Since the beginning of humanity, people have been trying to understand the secrets of matter. What is it made of, what are its constituents? Microscopes were first used in history to see cells of size about $50\mu m$. The observation of DNA requires further magnification down to the nanometer scale using electronic microscopes. Understanding the structure of atoms in terms of nuclei and then of nuclei in terms of quarks and gluons requires the use of particle accelerators that smash particles against each other to understand their structure, allowing to reach scales of atometers or 10^{-18}m. This is the case of the Large Hadron Collider (LHC) at CERN, Geneva, Switzerland, the highest energetic collider in the world to date.

The concept of atoms was already introduced at the time of antiquity by the Greek philosophers and scientists such as Democritos. They introduced it as the smallest part of matter that exists, and everything is made of atoms. Literally, atoms means “something that you cannot cut”. We had to wait for the beginning of 20th century, in 1910, to understand that atoms were composite objects made of nuclei and electrons. The structure of nuclei in terms of protons and neutrons was discovered in the 1940’s and the structure of protons and neutrons in terms of quarks and gluons in the 1970’s. At this stage, quarks and leptons (electrons, muons and taus) do not show any substructure and represent the fundamental states of matter. Everything in the universe is made of these simple constituents. The LHC can probe distances as low as 10^{-19}m due to its high energy but did not show evidence for existing substructures.

A view of the LHC is depicted in Fig. 1. It is located at the border between France and Switzerland close to Geneva. It can accelerate both protons and heavy ions such as Lead and Oxygen for instance. In case of protons, the center-of-mass energy is now 13.6 TeV, or 13.6 10^{12}eV (let us recall that 1eV is the amount of energy gained by an electron accelerated by a 1V battery), so about 7 times more energetic that its predecessor, the Tevatron, located at Fermilab close to Chicago in the USA. The circonference of the LHC is about 27 km and is located underground at a depth between 50 and 100 m. The power consumption is about 120 MW (for reference, a typical medium city such as Ann Arbor in the USA consumes about 200 MW per year). The energy per beam is very high, of the order of 800 MJ (1 MJ can melt 1 kg of copper).

The motivation to build up the LHC was to go back in time, and to reproduce conditions that are close to the big bang due to the high energy of the protons and heavy ions that collide. In that sense, the LHC is likely the hottest spot in the universe today. When two proton beams collide, they reach a temperature of 10^{17} degrees, but of course over a infinitely small area (for comparison, the temperature inside the core of the sun is about 10^{7} degrees, but of course over a large area). The conditions that are thus created at the LHC correspond to about 10^{-13} second after the big bang, right after the universe was born. It is also worth noting that the LHC is also probably the coldest spot in the universe as well since this is the largest refrigerator in the world. Superconducting magnets are used to keep LHC beams in orbit and they operate at a temperature of (-271) degrees Celsius. It takes about one month to cool down the LHC and about 10,000 tons of liquid hydrogen and 100 tons of liquid helium.

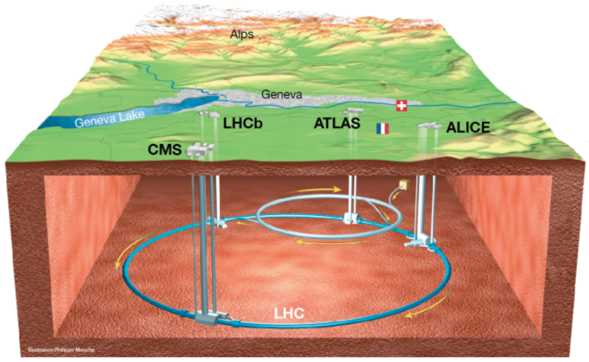

Figure 1: The LHC at CERN.

2 Doing physics at the LHC

Once a collision happens between protons or heavy ions at the LHC, the physicists want to learn what happened during the collision. The only way to do so is to measure all particles that are produced during the collision. A detector in nuclear or high-energy physics such as a detector at the LHC is thus similar to a digital camera with 100 megapixels that takes 40 million of pictures per second. Contrary to cameras, the detectors are sensitive to photons but also other kinds of radiation. The detectors at the LHC are thus the largest scientific instruments to track particles with micron precision over more than 50 meters with more than 100 million electronics readout channels.

Two general purpose detectors were built at the LHC, namely ATLAS and CMS. In addition, more dedicated smaller detectors such as ALICE, LHCb [1] (and in addition TOTEM, FASER, LHCf, etc... [2]) have more dedicated physics goals such as the study of heavy ion collisions and of b quark physics. ATLAS is the biggest detectors and represents about half of the vertical size of Mount Rushmore in the USA. The CMS detector is the heaviest one and weights about 30% more than the Eiffel tower in Paris. These detectors are huge like cathedrals built nowadays to study the heart of matter.

The general principle of a detector in nuclear and high energy physics is illustrated in Fig. 2. The idea is that different amount of material is needed to stop and measure the energy of particles according to their types. The first kind of detectors, very close to the interaction point, is usually composed of tracking detectors (Silicon, transition radiation detectors, etc...) that allow to measure precisely the trajectories of charged particles in a magnetic field produced by a solenoid, and also to know the point of interaction. The next layer includes the electromagnetic calorimeter where electrons and photons can be absorbed and measured, followed by the hadronic calorimeter where heavier particles such as protons, neutrons can be measured. Muons interact much weaker and require much more material to be detected and measured. This happens in the muon spectrometer where muon tracks can be reconstructed, allowing to know the muon energy via their curvature in the magnetic field. Neutrinos cannot be detected directly in the detector (most of them cross the earth without being stopped), but appear as missing transverse energy.

The amount of data collected at the LHC is huge and requires dedicated thousands of computers to be analyzed. Typically, the data collected at the LHC would fill 2 million DVDs per year. Hundreds of computers around the world are integrated together as a grid allowing to analyze the data everywhere. When protons collide, the actual collisions occur between their constituents, namely quarks and gluons. We cannot control which interaction happens but we can only record data and figure out what really happened. In the next section, we will discuss how we can understand the proton structure by analyzing data at the LHC.

3 The proton structure

As we mentioned already, the LHC can collide protons or heavy ions, and we will focus in this short report on proton proton interactions. Colliding protons allows understanding in detail their structure as illustrated in Fig. 3. The common knowledge about protons is that they are the constituents of nuclei, together with neutrons, and have a size of about 1 fermi (10^{-15} m), so about 1/1000 the size of the hydrogen atom. They are made of two up quarks and one down quark. At the LHC, the proton structure is much more complicated. Protons appear differently according to their energy (see Fig. 3). Q^2 is the resolution power (like a microscope). The higher the energy of an accelerator is, the higher values of Q^2 and the smaller distances that it is possible to reach. x is the momentum fraction of the proton carried by the quark or gluon that interacts. At high x, we see that the proton structure is dominated by the two up and one down quarks (with in addition some quark-antiquark pairs), whereas, at low x, the proton structure is completely dominated by gluons, The gluon density can get very large. In this kinematical region, new phenomena will appear. Let us give an everyday analogy and imagine the metro for instance in Paris at peak hours. It is completely full and, if the metro brakes for instance, all people in the metro will move together in a coherent way. It means that the behavior of people is somehow correlated. It is the same for the gluons inside the proton. The gluon density is so large that gluons can show a coherent behavior. It means that, when another gluon hits the high-gluon density proton, the gluons will behave coherently, and the cross section will not be the sum of interactions with one single gluon, but lower. This phenomenon is called saturation and is one of the goals of the LHC [3]. We can use protons to probe it, or even better higher density objects in terms of gluons such as Lead ions. The observation of the modification of the evolution equation of chromodynamics including the saturation effects will be a fundamental discovery at the LHC (and later on at the Electron Ion Collider to be built at Brookhaven National Laboratory in the USA).

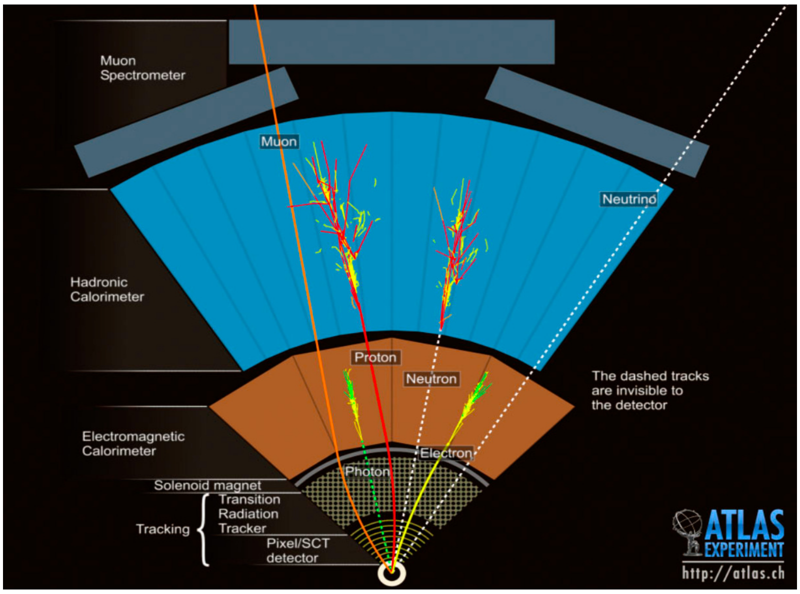

Figure 2: Principle of a detector in high energy physics (courtesy of the ATLAS collaboration).

4 Diffractive and photon-induced processes

In this section, we will discuss some very strange events that appear every day at the LHC in proton-proton collisions. In some events, the protons may remain intact after the collision (they lose part of their energy) and additional particles are produced. An everyday analogy would be an accident between two large trucks (the protons) that lead to one or both trucks remaining intact, and in addition to the production of smaller cars. There are two consequences. The first one is a pure quantum effect since the energy lost by the protons can be transformed into matter, and additional particles can be produced in addition to the intact protons. The second one is that we use the magnets of the LHC as a spectrometer, and the scattered protons will deviate slightly from the beam in the magnetic field since they lost part of their energy. This allows to detect and measure the scattered protons slightly away from the beam in dedicated detectors called roman pots

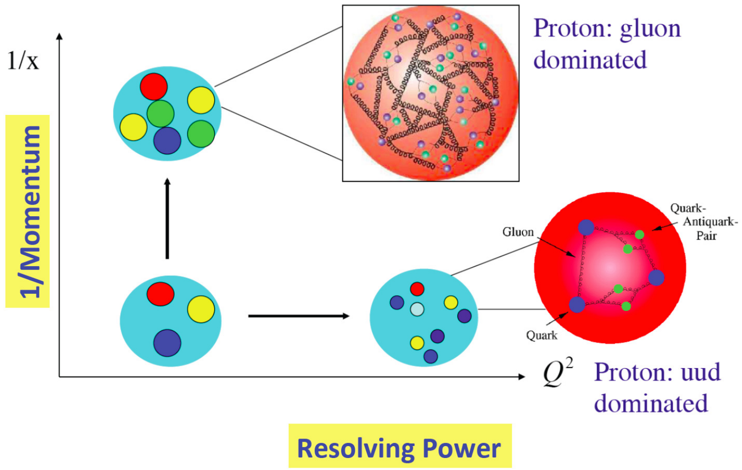

Figure 3: Proton structure in the plane momentum versus resolution power.

that can go very close to the beam. Such detectors were installed by the TOTEM and ATLAS collaborations at the LHC.

A special category of these events can be due to elastic interactions. In elastic events, protons are intact after collision and nothing in addition to the two protons is produced ($pp \to pp$). Protons are scattered at some angles and can lose some momentum as in the pool game where balls are hit without being destroyed. In order to explain that the protons remain intact after collisions from the point of view of quantum chromodynamics, there must an exchange of a colorless object between the two protons. A gluon carries a color and an anti-color, and we thus need to exchange at least two gluons. An exchange of an even number of gluons (2, 4, etc) is called a pomeron and of an odd number of gluons (3, 5, etc) an odderon [4]. Before the LHC, the odderon was predicted to exist but there was no experimental evidence for its existence. It is worth nothing that the existence of the odderon predicts a difference between elastic pp and $\bar{p}p$ cross sections. In order to compare both kinds of interaction, we used the pp data from the TOTEM collaboration at 2.76, 7, 8, and 13 TeV and the $p\bar{p}$ data from the D0 collaboration at 1.96 TeV [5, 6, 7]. After extrapolating the TOTEM data down to 1.96 TeV, the comparison between pp and $p\bar{p}$ interactions is shown in Fig. 4 and we see a clear difference between the two kinds of interactions. This led to the discovery of the odderon published by the D0 and TOTEM collaborations [8, 9].

The events with intact protons after interaction also allow us to look for “new” physics with unprecedented precision. Exchange of photons can occur between the two protons as shown in Fig. 5, left. This figure is called a Feynman diagram and illustrates the interaction with time increasing from left to right. It means that quasi-real photons are emitted by the two protons (they can remain intact after interaction since photons are colorless objects). They interact and can produce new particles (via loops or resonances) that have not yet been observed until now. This is the case of "axion-like particles" that could be candidates for dark matter in the universe. This new particle can itself decay into two photons, and after interaction, we thus have two intact protons and two photons [10]. Let us stress that the interaction between two photons (or light-by-light scattering) is not an obvious process. It is a pure quantum effect that does not exist at our everyday scale (the light from a light bulb does not interact with the light from another bulb). The sensitivity in the $\gamma\gamma$ to axion coupling versus axion mass is shown in Fig. 5, right and shows in grey the possible gain of sensitivity at the LHC using the measurement of tagged protons and two photons compared to the present situation [11]. This has already been searched for recently by the CMS collaboration at the LHC [12]. It is worth mentioning than it is also possiible to look for the production of pairs of W and Z bosons, $t\bar{T}$, γZ vis $\gamma\gamma$ interactions [13, 14, 15].

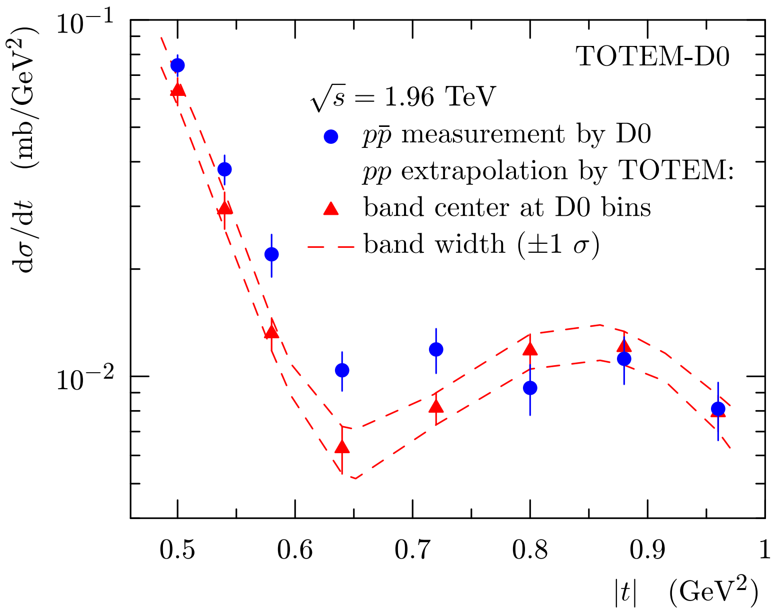

Figure 4: Comparison of elastic cross section between proton-proton and proton-antiproton interactions showing the discovery of the odderon.

5 Conclusion

In this short report presented as a general publiic talk during the ISMD 2024 conference in Gyöngyös, Hungary, we first described the LHC at CERN. We mentioned two physics topics related to the structure of protons and the possible search for saturation phenomena, as well as special (diffractive and photon-induced) events where protons can be intact after

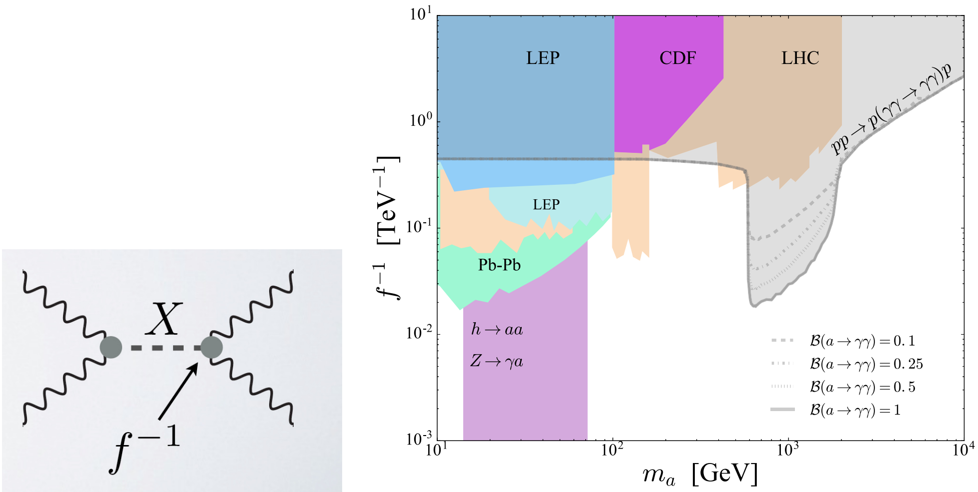

Figure 5: Left: Photon exchange process at the LHC - Right: Sensitivity to axion-like particle production in the coupling versus mass plane.

interaction. This led to the discovery of the odderon, and to unprecedented sensitivities to the production of new particles such as axions. The observation of such events would change the way we see the world. The LHC is now running and producing many data. Let us stay tuned and the LHC might still produce many surprises.

I would like to thank the organizers for providing such a possibility to give a general public talk, where many students from Europe connected by zoom on a week-end. This is a great opportunity to share our work with students.

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