FRONTIERS OF QCD

AT HADRON COLLIDERS

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Quantum Chromodynamics (QCD) is the theory which describes the strong interactions between quarks and gluons [1]. We will review some QCD-related results from the Tevatron, located at Fermilab in Batavia, IL, USA. The Tevatron is a proton antiproton collider with an energy in the center of mass of almost 2 TeV, which makes it the highest energetic collider in the world before the advent of the Large Hadron Collider (LHC).

▲ The Fermilab accelerator complex accelerates protons and antiprotons close to the speed of light. The Tevatron, four miles in circumference, is the world's most powerful accelerator, producing collisions at the energy of 2 tera electron volts (TeV). In a tiny volume, these collisions recreate the conditions of the early universe. Two experiments, CDF and DZero, record the particles emerging from billions of collisions per second.

The LHC is a proton proton (pp) collider with a center-of-mass energy of 14 TeV which produced its first collisions last year. We will first describe how the proton structure in quarks and gluons can be constrained using Tevatron data, and what can be expected at the LHC. Next, we will describe surprising events called exclusive diffractive events which will have important consequences at the LHC and especially for future physics projects in ATLAS and CMS, two main experiments at the LHC [1].

QCD studies at Tevatron and LHC

The principle of QCD studies and their interests are given in Figure 1. Protons can be considered as made of quarks and gluons. The proton structure is more complicated than the familiar structure in valence quarks *uud* (up-up-down). In most of the kinematical domain reached at Tevatron or at LHC, the proton constituents are the valence quarks, the sea quarks (pairs of quark-antiquarks) and the gluons. The two variables which characterize the interaction are x, the fraction of the proton momentum carried by the quark which interacts, and Q^2, the square of the energy transferred between both protons. Small x-values correspond to high quark/gluon density, each quark/gluon carrying a small fraction of the proton momentum. Q^2 acts like the resolution power of a microscope. When Q^2 gets larger, one sees a larger domain inside the proton, and the size of the quark/gluon is smaller. The LHC will allow probing scales in the proton which were never reached before, by accessing values of x down to 5×10^{-7} and Q^2 up to 10^8 GeV^2. For comparison, the Tevatron only reaches Q^2 up to 2×10^5 GeV^2.

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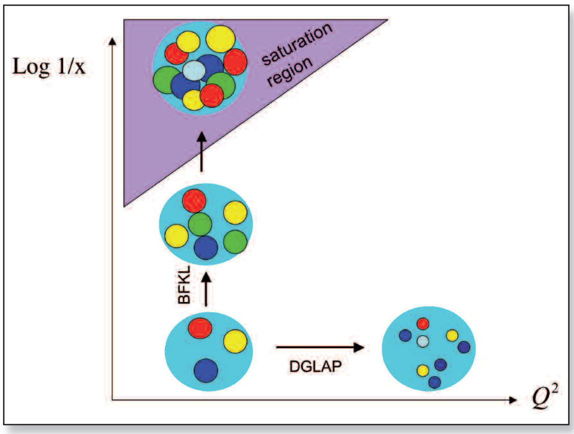
Two evolution equations can describe the proton evolution in Q^2 and x, respectively: the Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP) equation in Q^2 and the Balitski Fadin Kuraev Lipatov (BFKL) equation in x. Once the quark and gluon distributions are known for a given value Q_0^2, it is possible to use the DGLAP equation to know them at any Q^2 value, and to compare the results to the measurements performed at Tevatron, for example. We will describe some examples of such measurements that are fundamental to understand further the structure of the proton. It is also possible to predict the evolution in x using the BFKL equation. For a given Q^2, one looks at the proton for a given value of the microscope resolution, *i.e.*, for a given area inside the proton. When x decreases, the number of gluons increases. At some point, the number is so large that they start overlapping each other, and one can no longer neglect the interactions between the different gluons. This is the saturation domain. One of the challenges for the LHC is to see this new domain where the standard evolution equations do not hold.



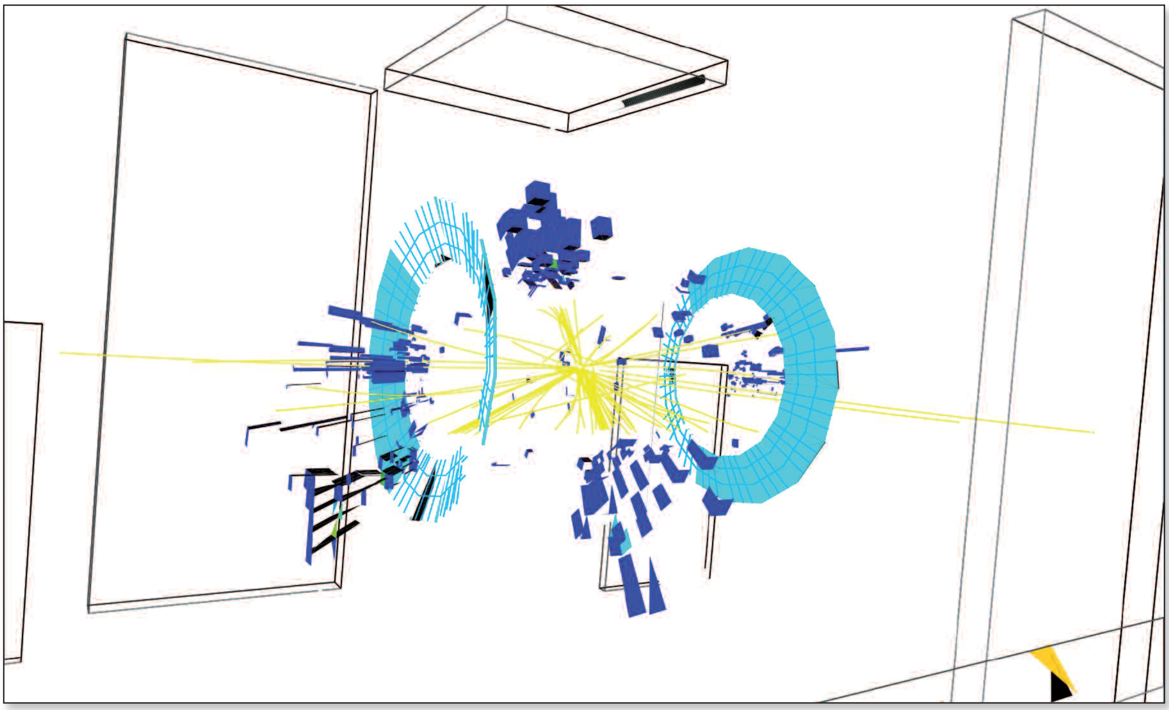
▶ **FIG. 1:** QCD at hadronic colliders. Here x is the fraction of the proton momentum carried by the quark which interacts, and Q^2, the square of the energy transferred between both protons (see text).

Constraints of quark and gluon structure

The first measurement sensitive to the proton structure performed in the two experiments at the Tevatron (called D0 and CDF) is the inclusive jet cross section. The event showing the highest jet transverse momentum is shown in Figure 2. We see that there are two 'jets', bunches of particles originating from the hadronization of quark and gluons in dark blue in the lower and upper part of the detector. The protons were completely destroyed and the available energy of about 2 TeV was spread in the two jets and the dark blue proton remnants are seen on the right and left sides of the detector. The transverse momentum of each jet is of the order of 600 GeV, and the dijet mass of 1.2 TeV, which makes it one of the highest mass objects ever produced in particle accelerators.

This kind of events is sensitive to beyond-Standard-Model effects such as quark substructure and allows constraining directly the structure of the proton in quarks and gluons since the rate of jet production is directly related to it. Calibrating precisely the jet energy (with a precision of about 1%) using the energy balance in very clean events, where only one photon and one jet are present, is quite a complicated and challenging task but is fundamental to get a precise measurement of the jet cross section. Data are compared to DGLAP calculations and a good agreement is found over six orders of magnitude as shown in Figure 3 [2].

Let us mention that many other measurements such as dijet mass, multijet cross sections, jet shape, W and Z boson inclusive production cross sections can also further constrain the proton structure.



▶ **FIG. 2:** Event with the highest transverse momentum jets (in dark blue - D0 experiment)

How do the uncertainties on the proton structure affect the LHC potential?

Another question is whether the uncertainty in the proton structure and also of the QCD calculation can affect the LHC discovery potential. As an example, the cross sections for Higgs boson production are known precisely both for background and signal (typical uncertainties: 5 to 15%). However, to perform QCD calculations, perturbative developments in series of strong coupling constant are done which leads to additional uncertainties of about 9%.

On the other hand, the LHC discovery potential (supersymmetry, Higgs boson, extra dimensions) can be affected if the background is poorly known because of the uncertainties on the proton structure. As an example, we can quote the effect of new interactions and extra dimensions, which might be of the same order as the present gluon and quark density uncertainties for some values of the parameters.

Mueller-Navelet jets

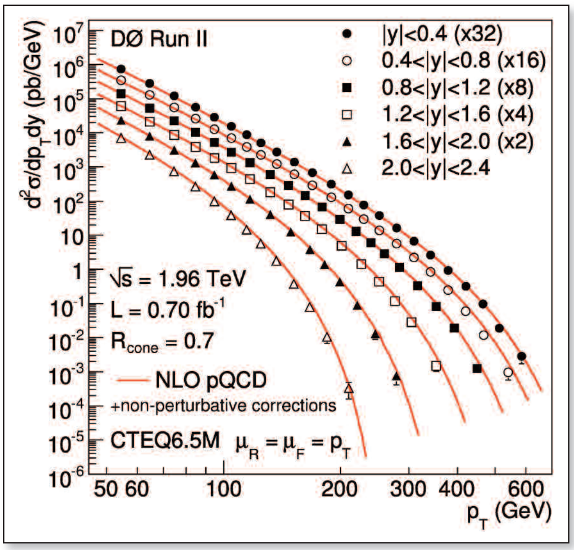
Mueller-Navelet jets are jets produced in *pp* collisions, requiring these two jets to be as far away as possible in polar angle, and to have about the same transverse energy. The DGLAP evolution equation ensures that the gluons emitted between these two jets are ordered in transverse energy. Since the two jets have about the same values of transverse energy, the probability that gluons can be emitted following the DGLAP equation is very small. On the contrary: the BFKL prediction is expected to be higher. Another easier observable is the measurement of the difference in azimuthal angle $\Delta\varphi$ between the two forward jets. Since there are few gluons emitted for the DGLAP evolution, $\Delta\varphi$ is peaked towards π whereas the BFKL expectation will lead to a flatter distribution. This measurement will be performed at Tevatron and LHC and can be a test of BFKL resummation effects as well as saturation phenomena [3].

Interest of exclusive events

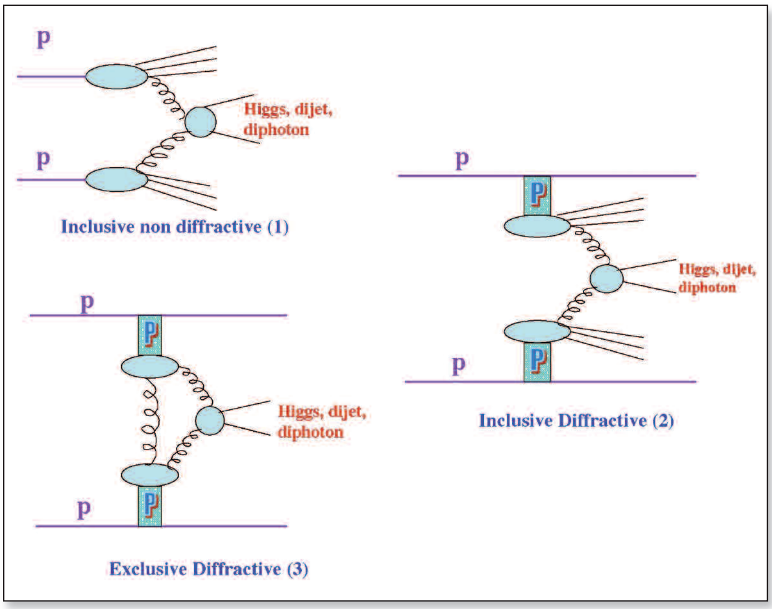
Before discussing exclusive events, let us introduce diffractive events. In most events, the proton is completely destroyed after the interaction and we observe only part of the proton remnants directly in the detector. In about 1% of the events at Tevatron, the situation is completely different: no energy above noise level is deposited in the direction of the proton or antiproton. This can be explained if the proton stays intact after the interaction. These events are called "diffractive".

A schematic view of non-diffractive, inclusive and exclusive diffractive events at Tevatron or LHC is displayed in Figure 4. The upper left plot (1) shows the "standard" non diffractive events where the Higgs boson, the dijet or diphotons are produced directly by a coupling to the proton and shows proton remnants. The right plot (2) displays the standard diffractive exchange where the protons remain intact after interaction and the total available energy is used to produce the heavy object (Higgs boson, dijets, diphotons...) and the remnants. The third class of processes is displayed in the bottom left figure (3), namely the exclusive diffractive production. In this kind of events, the full energy is used to produce the heavy object and no energy is lost. It means that for this kind of events all particles produced in the final state can be detected, for instance the final state protons and the Higgs boson [4].

There is an important consequence for the diffractive exclusive events: the kinematical properties, such as the mass of the produced object or its spin can be computed very precisely using the information on the intact protons. As an example, the mass of the Higgs boson if produced in this way can be computed with an accuracy of 2 to 3% [4].



◄ **FIG. 3:** Jet cross section as a function of jet transverse momentum in six bins corresponding to different jet angles.



▼ **FIG. 4:** Scheme of non diffractive, inclusive and exclusive diffractive events at the Tevatron or the LHC

Exclusive events at Tevatron

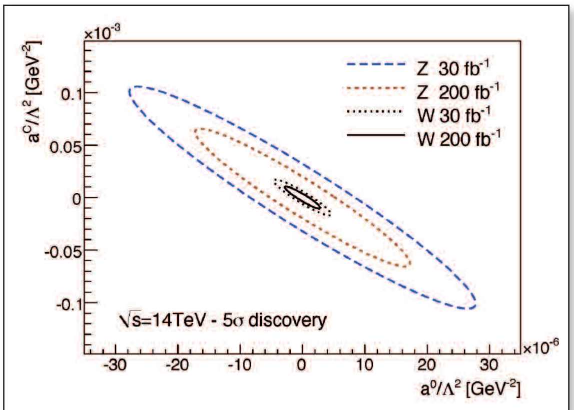
The CDF collaboration searched for exclusive events in many different channels and especially measured the so-called dijet mass fraction in dijet events – the ratio of the mass carried by the two jets produced in the event divided by the total mass – when both protons are intact in the final state [5]. The diffractive exclusive events appear when the dijet mass fraction is close to 1 (we recall that in exclusive events, only two jets are produced and nothing else). Adding exclusive events to the distribution of the dijet mass fraction leads to a good description of CDF data [6].

Exclusive Higgs production

One special interest of diffractive events at the LHC is related to the existence of exclusive events and the search for Higgs bosons at low mass in the diffractive mode especially in the supersymmetric scenario, an extension of the Standard Model in particle physics. Many studies were performed recently [4,7,8] to study in detail the signal over background for supersymmetric Higgs boson production in particular, and most of the supersymmetric parameter space can be covered using the first years of data taking at LHC.

Photon-induced processes

Photon-induced processes at LHC, and especially *WW* boson production [9,10], are especially interesting. The cross sections of these processes are computed with high precision using Quantum Electrodynamics (QED) calculations, and an experimental observation leading to differences with expectations would be a signal due to beyond-Standard-Model effects. The experimental signature of such processes is the decay products of the W boson in the main ATLAS or CMS detectors (two main experiments at LHC) and the presence of the intact scattered protons in the final state.
New physics beyond the Standard Model can manifest itself as a modification or appearance of *W* or *Z* boson couplings such as the triple $WW\gamma$, $ZZ\gamma$, or quartic $WW\gamma\gamma$, $ZZ\gamma\gamma$ couplings. It is worth noticing that many observed events are expected at high energy where beyond-Standard-Model effects are expected. The present sensitivity on quartic couplings can be improved by almost four orders of magnitude at LHC using the full luminosity as shown in Figure 5 [9], and it will be possible to test the Higgsless or extra dimension theories where these couplings appear naturally.



► **FIG. 5:** Discovery potential on new quartic $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings using the data at the LHC [9].

Future Detectors at LHC

To perform the potential studies described above, the ATLAS and CMS collaborations have the project to install forward detectors at 220-240 and 420 m allowing to measure precisely the position and arrival time of the intact protons in the final state. Timing detectors are also especially interesting for medical applications since they would allow improving the present resolution of the PET imaging detectors by one order of magnitude. ■

About the author

Christophe Royon is Research Director at the Service de Physique des Particules, Institut de Recherche Fondamentale sur l'Univers du Commisariat a l'Energie Atomique in Saclay France. He is member of the D0 collaboration at the Tevatron, Fermilab, Chicago USA and the ATLAS collaboration, CERN, Geneva, Switzerland. He performed his PhD in the H1 experiment at HERA on the first measurement of the proton structure function at low *x*. He was convener of the muon, QCD, and jet energy scale groups in the D0 experiment and is now the convener of the calorimeter group in the D0 experiment and the co-coordinator of the ATLAS Forward Physics project with Prof. Brian Cox and Prof. Stephen Watts of the University of Manchester.

References

[1] M. Boonekamp, F. Chevallier, C. Royon, L. Schoeffel, *Acta Physica Polonica* **B40**, No. 8, 2239 (2009).

[2] D0 Collaboration, V.M. Abazov *et al.*, *Phys. Rev. Lett.* **101**, 062001 (2008); CDF Collaboration, A. Abulencia *et al.*, *Phys. Rev. D* **75**, 092006 (2007).

[3] A.H. Mueller and H. Navelet, *Nucl. Phys. B* **282,** 727 (1987); C. Marquet, C. Royon, *Phys. Rev. D* **79**, 034028 (2009) ; O. Kepka, C. Marquet, R. Peschanski, C. Royon, *Eur. Phys. J. C* **55**, 259 (2008).

[4] M. Boonekamp, R. Peschanski, C. Royon, *Phys. Rev. Lett.* **87**, 251806 (2001); *Nucl. Phys. B* **669**, 277 (2003); V.A. Khoze, A.D. Martin, M.G. Ryskin, *Eur. Phys. J. C* **19**, 477 (2001); *Eur. Phys. J. C* **23**, 311(2002).

[5] CDF Collaboration, *Phys. Rev. D* **77**, 052004 (2008).

[6] O. Kepka, C. Royon, *Phys. Rev. D* **76**, 034012 (2007).

[7] M. Boonekamp, J. Cammin, S. Lavignac, R. Peschanski, C. Royon, *Phys. Rev. D* **73**, 115011 (2006).

[8] B. Cox, F. Loebinger, A. Pilkington, JHEP 0710 (2007) 090; S. Heinemeyer *et al.*, *Eur. Phys. J. C* **53**, 231 (2008) .

[9] O. Kepka, C. Royon, *Phys. Rev. D* **78** (2008) 073005; E. Chapon, O. Kepka, C. Royon, e-Print: arXiv:0908.1061; eprint:arXiv:0912.5161.

[10] T. Pierzchala and K. Piotrzkowski, arXiv:0807.1121.