CHAPTER 1

Introduction

The Standard Model of particle physics is built on top of two cornerstones – two quantum field theories: first one providing a unified approach to the weak and electromagnetic interactions, the second describing the strong and nuclear interactions. The latter of these is called **Q**uantum **C**hromo-**D**ynamics (QCD). The fundamental bricks of the hadronic matter are quarks and the strong force is mediated by gluons. QCD describes the way in which quarks and gluons interact with each other to create particles that could be observed experimentally, e.g. protons, neutrons and pions. It explains also how the nucleons form an atomic nucleus. QCD is a quantum field theory with a vast number of effects and processes that form a complicated dynamical picture of the internal structure of hadrons. Among others it comprises: confinement, asymptotic freedom, approximate chiral symmetry, axial vector anomaly, multiparton interactions, higher twist effects, saturation, and many more. With such a rich environment, experimental studies of QCD require measurements of many observables at different kinematical regimes to distinguish among various effects.

The **L**arge **H**adron **C**ollider (LHC) allows to study QCD at energies previously inaccessible. During Run1, described in this work, these energies for proton–proton collisions were between 0.9 and 8 TeV. Moreover, the **C**ompact **M**uon **S**olenoid (CMS) experiment provides a very wide detectors coverage that enables particles detection in a range spanning for $\sim$20 units in pseudorapidity. Therefore particles emitted at low angles with respect to the beam pipe can be measured. Such particles are produced in a number of QCD processes. Some of these processes are mediated by vacuum quantum number exchange called pomeron. Therefore with an access to the forward rapidities soft and hard diffractive processes can be effectively studied. Also the low-x parton distribution functions can be probed e.g. via a cross section measurement for the forward jets production. Moreover, studying correlations between production of objects at various rapidities, evolution of QCD (in x or Q^2) can be analyzed and an access to a gluon saturation region can be obtained. Measurement of an activity in the forward region can also be used to study underlying event, especially multiple parton scattering and formation of the proton remnant. Finally, the forward energy flow and the forward particle production can be used to tune hadronic models of ultra-high energy cosmic rays interactions with atmosphere.

A vast number of topics that can be studied with observables defined by an activity at large pseudorapidities triggered a creation of a dedicated **F**or**W**ar**D** **P**hysics **A**nalysis **G**roup (FWD PAG) at CMS. This paper presents main activities and results obtained within the group using data recorded during LHC Run1 – data taking period which started in 2009 and finished in 2013. Author of this paper was closely involved in the definition of the FWD PAG physics programme. He was involved in the preparation of the dedicated triggers, simulations of physics events, definition of the workflow including preparation and tests of the computing infrastructure, studies of the sensitivity of the forward detectors and eliminating technical problems. Then, first as a convener of the Exclusive

Production Physics Group, and next as a convener of the Low-x Group (both groups established in the frames of the FWD PAG) he was responsible for leading and coordination of a number of analyses based on observables measured with the forward detectors. In the Exclusive Group he was closely involved in the exclusive diphoton and dielectron production analysis and started search for exclusively produced $\pi\pi$ pairs. These analyses are described in the scope of this work. In the Low-x Group, author was the leader of the forward energy flow, forward jets and Mueller–Navelet dijets analyses. He had also an important input to the dijet K-factor and forward–central jets studies. All of them are included in this overview. Finally, during 2013–2015 period he was responsible for validation of the reconstruction of the data and Monte Carlo samples that were used in the analyses presented in this paper. During 2009–2011 he was working at CERN as a Fellow and then organized forward physics group at the Warsaw University.

According to the author's knowledge, this work is the first such extensive review of the forward physics results obtained on the data collected by the CMS during Run1 in the proton–proton collisions. Therefore the paper summarizes and concludes an entire chapter of the CMS physics programme. The presented results were officially released and published during 2010–2016 period. During preparation of this overview, some of the analyses still awaited for publication and were available as preliminary CMS results. A common aspect of all the analyses is a usage of the forward detectors located at high pseudorapidities close to the beam line. An arrangement of the chapters corresponds to the logic behind the scientific programme of the FWD PAG. Starting from the measurements of the activity caused by an underlying event, then moving to the hard scale observables (jets), selecting more specific diffractive events with a part of the detector devoided from any particles activity, finally looking at events with the exclusive production, that is with no additional activity except for the well-defined final state. In each chapter a short introduction to the theoretical and phenomenological problems is given, followed by an overview of the experimental results. Author is aware that there are many results on the forward physics from the other LHC experiments. However it was decided that this work should be dedicated exclusively to the results from the CMS experiment. Therefore no efforts have been made to include in the scope of this work the outcome of the other LHC experiments.

In the second chapter of this paper a description of the LHC operation in Run1 is given. A specification of the CMS detector is presented. An emphasis is put on subdetector systems located at large pseudorapidities, close to the beam line and thus exposed to a large irradiation. Also a triggering system, data acquisition and a software used for analyses are described. A short summary of the performance of the CMS in Run1 is also included and a detector system evolution during the data taking period is outlined.

The third chapter is dedicated to underlying event studies performed in the scope of the FWD PAG. Underlying event is all the activity present in an event not directly related to the hard interaction (better definition of a division line between an underlying event and a hard interaction is given within Chapter 3). A measurement of an underlying activity is important to approach a number of QCD effects, e.g. multiple parton interactions, rescatterings, proton remnant formation, final and initial state radiation, hadronisation etc. Experimental data are used as an input to models and simulations. They enable better tuning of generators and a better understanding of soft processes present in each event. Moreover, studies of an underlying event are a prerequisite to analyses of hard processes in which well-defined objects, e.g. jets are produced. These hard objects are measured on top of an activity produced in the detector by underlying event processes. Three approaches to the measurements of an underlying event at CMS are presented. These are: measurement of the energy flow in the Hadronic Forward calorimeter, measurement of the energy flow in the CASTOR calorimeter and measurement of the charged tracks multiplicity in events with a high-p_{T} leading object. Different observables and various samples of events included in the analyses provide an opportunity to make a distinction between miscellaneous effects and as a result to better tune Monte Carlo generators.

In Chapter 4 analyses related to the forward jets production are presented. At first an inclusive forward jets production cross section measurement is shown. Then an analysis that is looking at correlations between jets produced in the forward and in the central pseudorapidities is described. Next, an observable related to an activity in-between of the dijet pair produced with a large pseudorapidity separation is presented. Finally, an analysis of azimuthal angle correlations between pairs of jets emitted in the forward and backward directions (Mueller–Navelet dijets) is featured. The main goal of these analyses is to study QCD effects at low-x, especially effects corresponding to the QCD evolution in the regime described by the Balitsky–Fadin–Kuraev–Lipatov equations.

The fifth chapter is dedicated to analyses of diffractive events. Events with soft diffractive interactions are selected with a demand on a presence of a large rapidity gap produced by a colorless pomeron exchange. The cross section for production of various classes of events with a gap are calculated and compared to the predictions of soft diffraction models. Then, a hard diffraction is studied in events with a gap accompanying a production of high-p_{T} dijets or W/Z bosons. A special attention is paid to dijet events with a rapidity gap in-between the jets (jet-gap-jet topology). It is demonstrated that a proper modelling of observables in those events requires an introduction of effects described with the Balitsky–Fadin–Kuraev–Lipatov evolution equations. This could be the first observation of the BFKL effects at the Large Hadron Collider experiments.

In Chapter 6 interactions leading to an exclusive central production of various states are discussed. Not only QCD processes (pomeron–pomeron) but also pure QED processes (photon–photon) are responsible for the exclusive production. The following final exclusive states are analyzed: $\mu^+\mu^-$, $\mathrm{e}^+\mathrm{e}^-$, $\gamma\gamma$, $\pi^+\pi^-$ and $\mathrm{W}^+\mathrm{W}^-$. The last of these is especially interesting as it leads to the most stringent experimental limit for the anomalous quartic gauge coupling constant.

The last chapter summarizes the forward physics results obtained by the CMS Collaboration with the proton–proton collisions data from Run1.