Annex 3 to the „Wniosek o przeprowadzenie postępowania habilitacyjnego"

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# Summary of Professional Accomplishments

## Personal data

Name: Grzegorz Brona
Date of birth: 26 march 1980

## Diplomas and degrees

Doctor of Physical Sciences in Physics, obtained at University of Warsaw Ph.D. thesis title: „Hadron production and polarisation of gluons in the nucleon in the $\mu N$ interactions in the Compass experiment at CERN"
Promoter: prof. dr hab. Barbara Badełek
Reviewers: prof. dr hab.Jacek Turnau, prof. dr hab. Janusz Zakrzewski
Year of obtaining: 2007

Master in Physics (College of Inter-Faculty Individual Studies in Mathematics and Natural Sciences), Faculty of Physics, University of Warsaw

Master thesis title: „Search for pentaquark states in the COMPASS experiment"
Supervisor: prof. dr hab. Barbara Badełek
Year of obtaining: 2004

Master of Business Administration Diploma in Information Technology, Skarbek University (Wyższa Szkoła Handlu i Finansów Międzynarodowych im. Fryderyka Skarbka)
MBA thesis title: „ Computing GRID philosophy. From concept to implementation – an overview of the key problems"
Year of obtaining: 2008

## Information on the employment in research units

02.2008 - present: Faculty of Physics, University of Warsaw, assistant professor (adiunkt)

03.2009-03.2011: European Organization for Nuclear Research CERN, Switzerland, senior fellow

## Education

2004-2007: doctoral studies at the Faculty of Physics, University of Warsaw, PhD thesis with distinction

2006-2007: Master of Business Administration at Skarbek University (Wyższa Szkoła Handlu i Finansów Międzynarodowych im. Fryderyka Skarbka)

1999-2004: Master's degree at the Faculty of Physics, University of Warsaw, graduated with honors

1995-1999: XIV Liceum Ogólnokształcące im. St. Staszica w Warszawie (Stanisław Staszic Highschool in Warsaw)

## Awards

2016: Silver Medal of the 200th Anniversary of the University of Warsaw

2012: University of Warsaw Rector's 2nd Degree Individual Award for the research on quantum chromodynamics in proton-proton collisions at the CERN LHC

2012: Science Award of the 'Polityka' weekly

2011: University of Warsaw Rector's Team Award for the series of measurements verifying the predictions of the standard model for proton-proton collisions at the highest energies.

2004: Lech Michejda Award for the best master thesis

## Participation in- and organization of international and national conferences

1. 46th International Symposium on Multiparticle Dynamics, 2016, South Korea, "Recent results on forward physics and jets at LHC", international conference, presentation on behalf of CMS and ATLAS.

Grzegorz Brona

2. Low-x Meeting, 2016, Hungary, "Soft QCD measurements and diffraction in CMS", international conference, presentation on behalf of CMS.

3. 2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society "Collider Physics", 2016, "From exclusive production, through diffraction, to jets correlations - forward physics results from CMS", local conference.

4. Various faces of QCD 2 3rd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society, 2016, **organizer**.

5. Workshop on Forward Physics and High-Energy Scattering at Zero Degree, 2015, Japan "Diffraction at CMS", international conference, presentation on behalf of CMS.

6. 16th conference on Elastic and Diffractive Scattering, 2015, France, "Review of CMS and TOTEM results on Multi Parton Interactions, soft QCD and diffraction", international conference, presentation on behalf of CMS and TOTEM.

7. XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects, 2015, USA, "Diffractive processes in pp collisions at 7 TeV measured with the CMS experiment", international conference, presentation on behalf of CMS.

8. LHC Working Group meeting on forward/diffractive physics, 2014, USA, "Recent CMS results on forward physics", international workshops, presentation on behalf of CMS.

9. XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects, 28.04-2.05 2014, Warsaw, international conference, **co-chair of the organizing committee**.

10. Low-X Meeting, 2014, Japan, "Multijet correlations at large rapidity intervals at CMS", international conference, presentation on behalf of CMS.

11. Workshop on Jet Vetoes and Jet Multiplicity Observables at the LHC, 2014, England, "Latest results on multi-jets production, and beyond-DGLAP (BFKL, saturation) studies with jets", international workshops, presentation on behalf of CMS.

12. Forward Physics at the LHC, 2013, Italy, "Forward jets, forward-central dijets and dijets with large rapidity separation", international conference, presentation on behalf of CMS.

13. International Conference on New Frontiers in Physics, 2013, Crete, "Forward physics at the CMS", international conference, presentation on behalf of CMS.

14. LISHEP, 2013, Brasil, "Forward Jets", international conference, presentation on behalf of CMS.

15. Low-X Meeting, 2012, Cyprus, "Recent CMS results on small-x QCD", international conference, presentation on behalf of CMS.

16. International Symposium on Multiparton Dynamics ISMD, 2012, Poland, "Forward jets, dijet correlations at large rapidity separation and V+jets production at the LHC", international conference, presentation on behalf of CMS.

17. Low-X Meeting, 2010, Greece, “Physics of forward jets at CMS”, international conference, presentation on behalf of CMS.

18. 2nd International Workshop on Multiple Partonic Interactions at the LHC, 2010, Scotland, “CMS results on diffraction”, international workshops, presentation on behalf of CMS.

19. The 2009 Europhysics Conference on High Energy Physics, 2009, Poland, “Mini review – hard diffraction and central exclusive production at LHC”, international conference, presentation on behalf of CMS and ATLAS.

20. Moriond QCD and Hadronic Interactions, 2007, Italy, “Measurement of the gluon polarization at COMPASS”, international conference, presentation on behalf of COMPASS.

21. Spin-Praha, Symmetries and Spin, 2006, Czech Republic, “ΔG/G measurement at COMPASS”, international conference, presentation on behalf of COMPASS.

22. Cracow Epiphany –Conference on Hadron Spectroscopy, 2005, Poland, “Search for $\Xi^-$ pentaquark at COMPASS”, international conference, presentation on behalf of COMPASS.

23. Cascade Physics – A New Window on Baryon Spectroscopy, 2005, USA, “Cascades in COMPASS”, international conference, presentation on behalf of COMPASS.

## Leading scientific projects

1. A grant from Foundation for Polish Science, HOMMING+ programm, 2012-2014, project: “Forward Physics - a New Window on the Quantum ChromoDynamics”.

2. A grant from National Science Center, Sonata-bis programm, 2013-2016, project: “Physics of high rapidities – a new way to study QCD with new data from the CMS experiment”.

## Academic and Research Career

## Master degree studies

In my third year of MA studies at the Faculty of Physics, Warsaw University, in 2002 I got involved in the work of the Warsaw-based physics group of the COMPASS (NA58) experiment, located at the Super Proton Synchrotron (SPS) Accelerator at CERN. The experiment began collecting data in 2002, and my first task was to test the stability of the data recorded by the experiment using the reconstructed $K^0_s$ mesons decaying in the $\pi^+\pi^-$ channel. At the same time, in summer 2002 staying at CERN I collaborated with the Italian COMPASS experiment group on the RICH (Ring Imaging Cherenkov detector) subsystem. Thus, I had the opportunity to familiarize myself with the COMPASS experiment both from the data analysis side and the detector hardware design. In 2003 I continued my cooperation with the COMPASS experiment. In the summer of that year I participated in the Summer Studies program at CERN. At that time, there were the first reports of experimental observations of the pentaquark state containing one strange quark [1-3]. This particle ($\Theta^+$) was observed at a mass of about 1540 MeV in the decay channel to $\mathrm{pK}^0$. With the prepared algorithms of neutral kaons reconstruction and the knowledge of proton identification using the RICH detector, I attempted to confirm the existence of $\Theta^+$ state using the COMPASS experiment data gathered from 2002 to 2003 (later also from 2004). In 2004 the analysis was extended to search for pentaquark states containing two strange quarks ($\Xi_{3/2}$). This happened after the publication of the NA49 [4] experiment on the observation of such states at a mass of about 1862 MeV. These particles should be visible in the following decay channels:

$$\Xi_{3/2}^{--} \rightarrow \Xi^-\pi^- \rightarrow \Lambda^0\pi^-\pi^- \rightarrow p\pi^-\pi^-\pi^-$$
$$\Xi_{3/2}^{0} \rightarrow \Xi^-\pi^+ \rightarrow \Lambda^0\pi^-\pi^+ \rightarrow p\pi^-\pi^-\pi^+$$
$$\overline{\Xi_{3/2}^{--}} \rightarrow \overline{\Xi^-}\pi^+ \rightarrow \overline{\Lambda^0}\pi^+\pi^+ \rightarrow \overline{p}\pi^+\pi^+\pi^+$$
$$\overline{\Xi_{3/2}^{0}} \rightarrow \overline{\Xi^-}\pi^- \rightarrow \overline{\Lambda^0}\pi^+\pi^- \rightarrow \overline{p}\pi^+\pi^+\pi^-$$

This part of my analysis required the development of optimal reconstruction techniques in the COMPASS experiment of baryons $\Lambda^0$ and cascade baryons $\Xi^-$. I also reconstructed the state $\Xi^0(1530)$, which decays in a channel identical to the decay channel of $\Xi_{3/2}^0$. Basing on the Monte Carlo simulations (PYTHIA 6.2) I calculated the efficiency of the reconstruction of the $\Xi^0(1530)$ baryon in the COMPASS experiment, which enabled me to estimate the cross section for the production of this hadronic state.

The search for pentaquark states ($\Theta^+$i $\Xi_{3/2}$) ended with a negative result. I have not observed statistically significant deviations from the predicted background distribution. Basing on calculated estimates of COMPASS reconstruction performance for state $\Xi^0(1530)$, I calculated the upper limit of the cross section for the production of $\Xi_{3/2}$ pentaquarks. It is 0.12-0.21 nb and depends on the assumed width of the hypothetical signal. The negative results of the COMPASS search for pentaquarks are in line with the results of a series of other experiments published in 2004-2010. These results questioned the observations of $\Theta^+$and $\Xi_{3/2}$ states (see, for example [5] for an overview). The results I obtained became the basis for my MA thesis: „Search for pentaquark states in the COMPASS experiment" [6]. They were also presented by me at two international conferences (nos. 22 and 23 in the conference list) and were used to prepare two articles [7-8].

As part of the research work related to the search for pentaquarks, I conducted a broad analysis of the performance of the COMPASS detector. During it I reconstructed a number of other mass states: $\rho(770)$, $f_0(980)$, $f_2(1270)$, $\mathrm{K}^*(892)$, $\mathrm{K}_2^*(1430)$, $\phi(1020)$.

## PHD studies

I started PhD studies in 2004. During my studies I was working with the Warsaw COMPASS experimental group. My activity in the COMPASS experiment was related to three areas:

1) Based on the experience gained during my Master studies, I continued to analyze the production of hadron states in the COMPASS experiment in the interactions of muons with hadrons. In particular (in addition to the new researches on channels of the pentaquarks decays) I conducted a study on the mass state $f_0(1710)$, which was observed (with a small events statistics) by other experiments in the decay channel to $K_s^0 K_s^0$. This state is suspected of being a glueball state. Unfortunately, the mass spectrum analysis did not reveal the presence of the $f_0(1710)$ state in the COMPASS data. However I observed a lighter mass state, $f_2'(1525)$.

2) The Warsaw COMPASS experiment group was responsible for constructing and implementing a new detector plane for the COMPASS setup This detector plane was based on the scintillation fiber technology and its main purpose was to improve the reconstruction of charged particles (including scattered muons) in the area close to the beam axis. In order to optimize the location of the new detector plane within the COMPASS experiment system, several Monte Carlo simulations were required. These studies were performed for various possible positions and configurations of the new detector. I was responsible for this work and recommendations for optimal configuration of the new detector plane.

3) The main analysis I have conducted in the scope of my doctoral studies was the determination of the polarization of gluons in nucleon, $\Delta G/G$ , from double spin asymmetries in deep inelastic scattering of polarized muons on a polarized lithium deuteride COMPASS target. Polarization of the gluons was determined by analysis of the photon-gluon fusion process, which was selected by a demand of the production of open charm mesons, $D^0$. My analysis was based on the COMPASS data from 2002-2004. The result was $\Delta G/G = -0{,}57 \pm 0{,}41(stat) \pm 0{,}17(syst)$ at energy scale of 13 GeV$^2$ and $x_g$ of approximately 0.15. It is worth adding that my analysis was one of the key analyzes of the COMPASS experiment. My role was to carry out all of its parts (events selection, method optimization, Monte Carlo studies, systematic uncertainty analysis, result interpretation).

The results of the research on the production of hadrons and the measurement of polarization of gluons $\Delta G/G$ using the channel with $D^0$ particles production were the basis for my PHD dissertation entitled: „Hadron production and polarization of gluons in the nucleon in the μ-N interactions in the COMPASS experiment at CERN" [9]. The dissertation was defended in October 2007, just three years after the start of my PHD studies. The dissertation received a distinction. The results were presented by me at two international conferences (no. 20 and 21 in the conference list), published in two conference articles [10-11] and a in a summary article [12].

## Post-doctorate activity

Since February 2008 I have been assistant professor at the Faculty of Physics, Warsaw University. Since the end of 2008 I was still active as a member of the COMPASS experiment group. At that time, I was finishing my activities in the experiment group. Among others I was performing, on data taken in 2002-2004, the new calculations of $x_g$ and the energy scale for the gluon polarization analysis in the open charm channel, using a weighting method that takes into account all sample selection cuts. I also conducted a part of the cross-check analysis for the $\Delta G/G$ measurement in the open charm channel using additional data from 2006-2007, and taking into account the Next-to-Leading Order (NLO) approach. I still supported this analysis to a limited extent in 2010, while formally no longer a member of the COMPASS team (the last presentation in the COMPASS experiment containing my new results took place in February 2011).

I was the tutor of a bachelor's thesis conducted by a student of the Faculty of Physics at the Warsaw University (Mr Maciej Misiura) in the scope of the COMPASS experiment. The subject was an analysis of new COMPASS data (2006) looking for potential glueball states decaying in $K^0K^0$ channel. The thesis titled „Study of the COMPASS spectrometer performance with K0s mesons and reconstruction of K0K0 pairs mass spectrum" was defended in 2010 at the Faculty of Physics, Warsaw University.

In February 2009, I left Warsaw for a two year post-doctoral internship at CERN in Geneva (Senior Fellow). The program allows to freely choose which experiment to join. My choice was for the Compact Muon Solenoid (CMS) experiment at the LHC collider. The main goal of the CMS was to search for the Higgs particle and manifestations of New Physics particles. The CMS physicists working in these areas are very numerous and I believe that joining such large research groups would not allow me to play a significant role in the team. That's why I decided to join the youngest and smallest research group in the CMS experiment - the Forward Physics group. The group's activity was linked to a CMS subdetector system located in the vicinity of the beam (so-called forward detectors). This location forces a special detector design (radiation resistance), and imposes limitations on the data analysis techniques (eg, pile-up rejection). The Forward Physics team was the only one in the CMS, that was not defined by a particular physic (eg, the search for Higgs bosons), but by a specific detection system, a good understanding of which allows to use it in a variety of analyzes. In my opinion, this group acted almost as a small independent experiment in the large CMS collaboration, and for that reason it seemed to me particularly interesting. Overview of the group's activities during the LHC Run1 is presented in the next chapter of the presentation describing scientific achievements.

At the time I joined the Forward Physics group, it was at the organizing stage - only about 15 people were actively participating. Physical analyzes had not yet been fully defined, and detectors had not been tested under operational conditions. The first data taking by the CMS experiment was planned for 2008, but due to a major accident the launch of the LHC was postponed to the end of 2009. When I joined CMS Forward Physics, I had a period of about 9 months, during which I was able to support the organization process. It is worth adding that during most of my stay at CERN, I was the only direct CERN employee working in the Forward Physics group. Within the Forward Physics group, there are three subgroups - Exclusive Physics, Diffractive Physics and Forward Jets (since the end of 2009).

My activities in the Forward Physics group prior to the start of data collection by CMS:

1. From June 2009 to November 2009 I organized the Exclusive Physics subgroup. I became its first convener. I was involved, among others, in preparation of analyzes of

the exclusive production of photon pairs and exclusive hadron production. In the first case, I was involved in the analysis of the performance of the proposed triggers selecting exclusive production and checking the effects of the pile-up on the analysis. In the latter case, I proposed analyzing the exclusive production of pairs of pions and the search for a particle $\rho(770)$ in this decay channel - at the beginning of 2010, after the first physical data was collected by the CMS experiment, I was the first person to reconstruct $\rho(770)$ and then showed the effects of the exclusivity cuts on its selection. The analyses started within the group had their results published [13-17]. Within organizing the work of the subgroup, I presented a plan of its activities at one international conference (No. 19 in the conference list) and presented it in a post-conference article [18].

2. I demonstrated the need to introduce new triggers dedicated to Forward Physics. Then I was responsible for defining and software implementing of CMS triggers that trigger data collection for collisions with high activity in the forward detectors area. In particular, I prepared triggers that allowed for effective record of events with jets and events where there are correlations between objects with high separations in rapidity. The implementation of triggers I tested at Monte Carlo level was accepted by the CMS team.

3. On behalf of the Forward Physics group I coordinated exercises conducted in the CMS collaboration, which were designed to prepare teams to perform analyzes on actual data. During the exercises, the collections of events generated by the Monte Carlo generators were analyzed. The exercises mainly served to test the cooperation between different parts of the global computer infrastructure (Tier 2 level) and data reduction methods to the so-called skims. All the goals of the exercises that I had set for the Forward Physics group were achieved. Thanks to that, the first public presentation of the real results of the Forward Physics group took place very quickly (April 2010).

4. In October 2009, a Forward Jets subgroup was created, aimed at the analysis of jets in the forward detectors. I became the first convener of this group and responsible for creating and defining analyzes to be performed in its structure. I proposed that the group's activities be extended by measuring forward energy flow. This is a measurement on the one hand necessary for a good understanding of the production of jets, and on the other hand it addresses issues related to multiparton interactions and underlying event. I conducted the first Monte Carlo-level analysis of the above issues.

In December 2009, data at 0.9 TeV and 2.76 TeV were recorded by CMS. I was responsible for supervising the Quality Data Monitoring (DQM) of the Forward Physics group and then for reconstructing and presenting the first jets that were recorded at high rapidities. It turned out that the essential group of the reconstructed jets did not correspond to real physical objects, but to the effects of read-out electronics excitations by single particles. These were called fake jets. This effect introduced a strong background to the measurements of forward activity. I focused myself in the following months on its understanding and elimination through appropriate reconstruction algorithms.

In the spring of 2010 data collection began at CMS at 7 TeV energy. My activity in the group in 2010-2011 (during CERN internship) was focused on:

1. Performing a measurement of the energy flow in the Hadronic Forward (HF) calorimeter area located at high rapidities. I was the coordinator of the analysis and the editor of the summary note on the basis of which the measurement results were made public. I defined observables, developed algorithms for analysis, and conducted extensive research on systematic errors. Initial results of the analysis were the first physical results of the whole CMS experiment for collision energy 7 TeV presented in public. This happened at XVIII International Workshop on Deep-Inelastic Scattering and Related Subjects, April 2010. I also presented the results personally at one international conference (No. 17 in the conference list) and described in article [19], which presents the measurement of energy flow in the HF calorimeter for collisions energy 0.9 and 7 TeV.

2. Measuring the inclusive production of jets recorded in the HF calorimeter. I was the coordinator of this analysis, directly responsible for the definition of observables, conducting systematic studies, particularly those related to corrections incorporating detector effects and interpretation of results. My knowledge of the influence of fake jets was important here while they had to be effectively removed. In addition, I studied effects related to overlapping multiple collisions (pile-up effect). The analysis ended with the publication in 2012 of an article [20].

3. Participation in the analysis of the energy flow in the CASTOR calorimeter area (detector located near the beam, in rapidity area higher than the HF detector). Originally, the results of this analysis were to be made public together with the results of the HF detector analysis in 2010-11. My role was to coordinate the methods used and the approach to systematic errors between the HF and CASTOR measurements. Finally, a decision was made to conduct additional studies on the CASTOR detector performance and therefore publication of the results was not forthcoming until 2013 [21].

4. Supervising the triggers work for the Forward Physics group. With the increase in LHC luminosity, triggers had to evolve to adjust the amount of data passed to the Data Acquisition System (DAQ). In 2010-2011 I was responsible for monitoring and making the necessary changes to the trigger layout.

5. Participating in the analysis of the production of pairs of jets, one of which is emitted centrally and one forward. This analysis covers the essential part of the analysis of the production of inclusive forward jets (point 2 above). My role was to prepare some of the selection algorithms and to make a comparison between the two analyzes. The results of the analysis are described in the article [20].

6. Participation in the analysis of jets highly separated in rapidity, so-called Muller-Navelet jets. The triggers proposed and introduced by me in 2009, allowed in 2010 and 2011 to gather a significant sample of events with jets highly separated in rapidity (up to 9 units). This made it possible to analyze correlations between such jets, which is an important measurement for QCD [22]. In 2011, I began analyzing the data collected by the experiment together with my M.Sc. student Maciej Misiura. In 2012, Mr. Maciej

Misiura presented his MA thesis entitled "Studies of jets production separated by a large rapidity interval with the CMS data", and then he was admitted to doctoral studies, which continue under my supervision - the PhD thesis is devoted to the extension of analysis to events with Mueller-Navelet jets collected In 2015, with the collision energy of 13 TeV. The title of the thesis is "Quantum chromodynamic tests at high pseudorapidities in the CMS LHC experiment", and the defense is scheduled for early 2018. The results of the 2011 correlation analysis between Mueller-Navelet jets for collisions at 7 TeV were published in 2016 [23].

7. Participation in the so-called dijet k-factor analysis, which based on a comparison of the cross-sections for the production of pairs of high energy jets without and with an additional jet emitted between the pair. This analysis used both the dedicated triggers developed by me, and standard jet triggers for central jets selection. I got engaged in, among others, the preparation of a method of combining the results from both the triggers. The results of the analysis were published in [24].

8. I worked closely with the Diffractive Physics subgroup, particularly in the field of HF detector performance. These detectors, which I examined in the analysis of forward energy flows (point 1 above), are the basic detectors that make it possible to measure the large rapidity gap defining diffractive events. The Diffractive Physics subgroup was represented by me at that time at one international conference (No. 18 in the conference list).

During my stay at CERN I continued to play the role of the convener for Forward Jets group in 2010-11. This included, among others, organizing at least once every 2 weeks group meetings, preparing standard tools and recommended data usage methods, working with detector groups, especially those responsible for HF, CASTOR and ZDC detectors (third of the forward calorimeters). Also, considering that for much of the time between 2009 and 2011, I was the only direct CERN employee involved in the Forward Physics group, and that meant a continuous presence at CERN, I repeatedly represented the entire Forward Physics group at the CMS experiment forum. I coordinated the first working meetings between the CMS experiment and the TOTEM experiment, which in the long run led to intensified cooperation and a number of interesting results. In addition, I managed the Forward Jets group human resources and I took care of the CERN Summer Studies students assigned to the Forward Physics group (I defined the research projects for them). I stayed at CERN until June 2011.

Upon my return from CERN, I continued to work with the Forward Physics group within the Warsaw CMS group. In particular, until 2012 I was the head of the Forward Jets subgroup, and then by 2015 I was a Forward Physics representative in the CMS Physics Validation Team (PVT). The purpose of the PVT group was to verify the quality of the reconstructed data (after completion of CMS data taking in 2013, recorded events may have undergone several reconstructions after significant changes in the reconstruction software) and the quality of the Monte Carlo samples produced. My role was to check the quality of events produced for their usefulness in forward physics analyzes. My work for PVT group concluded with the start of PVT activity with new data collected in 2015 (collision energy of 13 TeV).

In the period 2012-2016 I continued to work on ongoing physics analyzes (most of the previously mentioned publications appeared in this period). I also focused on working with students of the Faculty of Physics, Warsaw University. During this period (as mentioned earlier) I was supervising the master's thesis and later the doctoral degree of Maciej Misiura. I also supervised the Bachelor Degree thesis of Piotr Olejniczak. "Research on the exclusive production of jets in the CMS experiment at the Large Hadron Collider" (thesis defended in 2011). His thesis was devoted to the study of the possibility of observing the exclusive production of pairs of jets, an interesting topic for that the observation of exclusive jets production allows to estimate the expected cross-section for the production of exclusive Higgs particles. The thesis has shown that pile-up at the LHC will effectively prevent the exclusive jets from being observed using the current CMS detection system. I was also the supervisor of M. Konrad Nesteruk's M. Sc. thesis. "Measurement of the energy flow at large pseudorapidities in pp and pPb collisions with the CMS at the LHC" (defense 2013). The thesis is an extension of the energy flow analysis in the area of the HF detector with new data. In particular, it refers to data from asymmetric collisions, ie, proton-lead. Also, Marek Walczak prepared under my supervision his master's thesis entitled "Search for Resonances in the Forward-Backward Dijet Mass Spectrum from 7 TeV pp Collisions at CMS". The subject of the study was the analysis of the mass spectrum reconstructed from two jets of high separation in rapidity. Thanks to the trigger implemented by me, the work could be based on an exceptionally high pairs of jets statistics, and thus let us look at the mass spectrum well above 1 TeV. After defending his master's thesis (2014), Mr. Walczak became my doctoral student. The topic of his dissertation (planned to open in early 2018) is the analysis of CMS data from collisions of heavy Ions at the LHC for reconstruction and study of ultraperipheral collisions with exclusive production of heavy mesons (J / psi, Upsilon). This topic is related to my co-operation with the CMS Heavy Ions Forward Physics subgroup.

In the period 2012-2016 I represented the Forward Physics group at fourteen international conferences (Nos. 10-16 and 5-8 and 1-3). Presentations included the Forward Jets subgroup activity (renamed Low-x QCD group in 2011), the Diffractive Physics subgroup activity, and reviewed the work of the entire Forward Physics group. In addition, in some cases, I was selected to represent not only the results of the CMS experiment, but also the ATLAS experiment (No 1 in the conference list) and the TOTEM experiment (No 6 in the conference list). I also published five conference articles [25-29]. I was co-organizer of two conferences: one international (no. 9 in the list of conferences), where I was a co-chair of the organizing committee and one Polish (no. 4 in the list of conferences).

In 2017 I focused on the preparation of monograph, which is the scientific achievement presented in the process of habilitation.

## Presentation of scientific achievements

**In accordance with the requirements of Article 16 (2) of the Act of 14 March 2003 "On scientific degrees and academic title and degrees and titles in the field of art" (Journal of Laws No. 65, item 595, as amended).**

As a scientific achievement I present monograph:

**„Forward Physics – a new window on high energy interactions. Results from Large Hadron Collider Run 1 data taking obtained with Compact Muon Solenoid experiment"**

published by the Publishing House of Warsaw University, Warsaw 2017, ISBN 978-83-235-2862-3, which I am the only author. The subject of the monograph is a comprehensive review of the results obtained by the Forward Physics group based on proton-proton collision data collected by the CMS experiment in 2009-2013. The presented results were published in the period 2010-2016. The choice of the subject of the monograph was dictated by my activity in the Forward Physics group, and in particular, being the convener of two research groups - Exclusive Physics and Forward Jets (later renamed Low-x QCD), where I coordinated and conducted a substantial part of the research work described.

The monograph was conceived as a compendium of knowledge about forward physics, which was studied in the CMS experiment using Run 1 data (2009-2013). The chapters, apart from the description of the experimental results, also have a theoretical-phenomenological introduction, in which a simple description of why given experimental studies are interesting is included. On the other hand, I tried to describe the basic tools used by the Forward Physics group in their analyzes (eg algorithms for selecting jets). The goal was to create a work that not only provides an overview of the results, but is also useful for those who do not have much experience in the field (eg students). Realization of this goal resulted in a significant increase of the volume of the monograph. Therefore I decided to focus solely on the results of the CMS experiment. The results of the other experiments, including the second large LHC experiment - ATLAS, as well as the results of collaboration between the CMS and TOTEM research groups, were omitted.

The monograph is composed of seven chapters: 1. Introduction, 2. Large Hadron Collider, Compact Muon Solenoid, and its forward detectors, 3. Underlying event, 4. Forward jets, 5. Soft and hard diffraction, 6. Exclusive production, 7. Summary. The monograph is written in English.

### Large Hadron Collider, Compact Muon Solenoid, and its forward detectors

The second chapter of the monograph describes the operation of the LHC accelerator during the so-called. Run 1, from its start in 2009 to the end in early 2013. A description of the evolution of the conditions of the accelerator's operation during this time is described. This evolution includes very rapid increase in luminosity, which directly influences the possibility of studies in the Forward Physics group - most of the analysis were possible only during the so-called low luminosity periods, and hence low pile-up.

Next, the Compact Muon Solenoid detector is presented, with particular focus on the detectors working near the beam (forward detectors). The construction of the two most important calorimeters of the Forward Physics group, namely the Hadronic Forward (HF) calorimeter and the CASTOR calorimeter, is described in detail. The data collected by these detectors are crucial for the analyses described in the monograph. As part of my work in the Forward Physics group, I worked closely with the groups dealing with both detectors. Inter alia I was involved in the Data Quality Monitoring (DQM) team in 2009 and 2010, which analyzes (both on-line and off-line) the work of all components of the detectors. Then, I was working with the Physics Validation Team (PVT), checking the quality of the Monte Carlo samples and data reconstruction. My work was focused in the PVT group on the stability of the forward detectors. Moreover, analyzes conducted in 2009-2016 in the Forward Jets group (eg forward energy flow analysis described in Chapter 3) were strongly related to the understanding of the operation of HF and CASTOR detectors during the LHC operation. Therefore, the presented description of both detectors also includes description of some problems arising during the data taking. In the case of HF these are single particles activating the detector read-out electronics and imitating large energy deposits in the HF active area, and in the CASTOR case this is the CMS magnetic field, which penetrates inside the CASTOR detector reducing the sensitivity of the calorimeter.

Other forward CMS detectors, including the Zero Degree Calorimeter detector (used mostly for heavy-ion data programm at LHC), BSC and BPTX detectors (which were part of the CMS trigger and beam monitoring system) as well as the TOTEM experiment system, which is located in the immediate vicinity of the CMS, are also presented in this chapter. As a part of my stay at CERN, I co-operated with experts from the TOTEM experiment, which led to joint data analyzes.

The last part of this chapter is dedicated to the system of triggering, processing, saving and sharing of the data. For the Forward Physics group, in particular the triggering system is very important. There are several reasons. In the case of exclusive events recording (eg exclusive production of lepton pairs, described in Chapter 6 of this monograph), the system of triggers must effectively select very rare collisions. In the case of minimum bias studies (eg forward energy flow analysis), the system of triggers must not introduce any bias to the recorded interactions. In the case of correlation studies between different objects (jets, rapidity gaps), the design of the trigger must lead to the selection of interactions that have very specific characteristics of the final state. The latter case is discussed in more detail in Chapter 4, which describes the study of the correlation between jets. I was involved directly in the definition of Forward Physics triggers (both within the Exclusive Physics subgroup and Forward Jets), and then responsible for implementation. In 2010 and 2011 I also supervised the work of triggers dedicated to the correlation studies.

**Underlying event**

The third chapter of the monograph is dedicated to the underlying event (UE) studies, which were conducted under my supervision in the Forward Jets group. An Underlying Event is defined at the parton level as all the activity originating from a given proton-proton collision except for the hard interaction. This activity is a result of a number of effects: multi-parton interactions, proton remnants, initial and final state radiation. In an experiment not partons but hadrons are detected. These hadrons are produced in a hadronisation of a number of partons, some of which come from the hard interaction but the origin of the rest is unknown. Therefore experimentally an UE cannot be directly distinguished from a hard interaction. Thus, different Monte Carlo models are used to study the UE and its decomposition to various subprocesses. The generated Monte Carlo events are passed through the hadronisation process and then compared with experimental results. To be able to tell more about the subprocesses forming the UE, the comparison must be carried out for the widest possible range of samples (defined by the different collision energies and different final state products observed). The models for the UE simulations included in PYTHIA and HERWIG programs are described in this chapter. These models contain a number of parameters that can be changed during the generation. The model with the set of parameters is called a "tune". The experimental results of the Forward Jets group, on the one hand are compared to different tunes, and on the other hand they allow groups of theorists and phenomenologists to obtain new, better sets of parameters. Good UE characteristics at the LHC energy are also required for other studies within the Forward Physics group. In particular, this applies to the forward jets analyzes. Jets should be reconstructed after subtracting UE activity, and this activity is particularly strong in the area near the accelerator beam, the forward area.

In the scope of the Forward Jets group (and next Low-X QCD group), a number of analyzes were carried out with the aim of the UE studies. As early as 2009, an analysis related to energy flow in the area of HF and CASTOR detectors began. This analysis (which I was leading) was aimed at exploring forward activity for different types of collisions (for different energies, and for different mean centralities, defined by selecting objects of different hardness in the final state). Activity was defined by energy deposits in calorimeters (in this area there are no tracking detectors). The analysis showed that none of the existing models or their variants (tunes) was able to describe simultaneously the results for all the samples tested. The tunes already encompassing some other LHC results (eg, activity analyzes in the central area of the CMS detector) works better. The experimental results were passed to the physics groups outside the CMS Collaboration, which are in the process of preparing new tunes. It was also interesting to compare the Monte Carlo predictions obtained with generators that were developed for describing cosmic ray interactions (EPOS, SIBYLL, QGSJETII). None of the programs has provided predictions in a satisfactory manner describing the results of the CMS. Chapter 3 also includes a description of the EU measurement using the so-called. leading objects. This method involves finding the object with the largest transverse momentum in a given event (single charged particle, jet) and then checking the activity in different areas of the CMS detector relative to the direction defined by the leading object. This method makes it possible to identify areas and observables that are more sensitive to specific components of the UE (eg, initial and final state radiations). This makes it possible to have an insight into the dynamics of the UE and the impact of different subprocesses. The results of the analysis have been widely presented in monograph.

**Forward Jets**

In chapter 4 analyzes related to the forward jets production at CMS are presented. The main goal of the Forward Jets group analyzes was to study QCD in the area of small x, and in particular to confirm the appearance of effects, which in their description require reference to the dynamics described by the BFKL equations (Balitsky-Fadin-

Kuraev-Lipatov). Both, the high collision energies available at the LHC and the wide experimental coverage of the CMS detector provide means to look for the BFKL evolution effects. The monograph describes a series of measurements related to jets recorded in the forward area of the CMS experiment (in the HF calorimeter).

The first described measurement is an analysis of the cross section for the production of inclusive jets in the region between 3 and 5 in rapidity. I was personally responsible for this analysis. As a result, a spectrum of jets in this area was presented and compared with a number of LO and NLO models. Unfortunately, the systematic errors that resulted from the uncertainty of the HF calorimeter energy scale, turned out to be so large that they did not allow to demonstrate the superiority of one model over another. As part of the analysis I conducted a series of studies on systematic errors (resulting from various aspects of the HF calorimeter design and operation) and theoretical uncertainties. In addition, I focused on investigating different methods for including improvements to the detector performance and corrections that bring results from a detector level to a hadronic level. Good understanding of both, systematic errors and methods of reducing the impact of CMS detector effects on the measurement result, proved to be extremely valuable for subsequent, less inclusive analyzes.

The next measurement presented is the correlation between the production of high rapidity jets (corresponding to the HF detector) and jets located in the central area of the CMS detector. With the selection of leading jets that are substantially separated from each other in rapidity, a kinematical space where additional jets or individual particles can be emitted is opened, and thus a whole set of effects affecting the observed jets can appear. As a result, it is expected that at least some of the theoretical models will show significant deviations from the measurement. Indeed, the consistency between model predictions and experimental data, even with a large systematic uncertainty present, is indeed much worse. In particular, most models provide predictions for much more central jets than it is present in the data.

The third measurement presented is based on a selection of two leading jets with a high separation in rapidity and checking the additional activity between those two jets. Additional activity is defined in this case as a presence of a third jet above a certain transverse momentum in the area of rapidities limited by the two leading jets. The cross sections are calculated for the production of events in which such additional jets appear and for the production of events where there are no such jets between the two leading jets. Dividing the cross sections calculated for both samples, most systematic uncertainties are canceled and thus the ability to test different hypotheses increases. Interestingly, models based on the DGLAP approach (in particular PYTHIA), perfectly describe the measurement results, whereas those based on BFKL (HEJ, CASCADE) are significantly different from the actual data.

The last presented measurement is the analysis of angular decorrelations (in the azimuthal angle) between the so-called Mueller-Navelet dijets. These jets in the case presented in monograph are defined as a pair of jets with transverse momentum exceeding 35 GeV and within the acceptance between -5 and 5 in rapidity. Among the many pairs of jets only pairs with the greatest separation in the rapidity are selected. The azimuthal decorrelations between these jets are produced by additional soft emissions, which are described by the BFKL equations. The final results of the angular decorrelation analysis were published in 2016. The experimental results are compared with model predictions from various Monte Carlo generators and with theoretical predictions (BFKL). In some respects, the description based on the BFKL equations seems best suited to the experimental results, while in others the DGLAP and BFKL models do not provide a fully satisfactory description. In order to finally answer the question of the significance of the BFKL effects, Mueller-Navelet dijets analysis is now extended to the data collected at higher collision energy (13 TeV). The analysis is conducted by my PHD student.

**Soft and hard diffraction**

The fifth chapter is dedicated to the description of diffractive interactions, both soft and hard diffractive component is presented. Diffractive events are selected in the experiment by selecting collisions with a large rapidity gap present. This gap is devoided of any recorded activity and should correspond to the exchange of the pomeron carrying quantum numbers of the vacuum. This definition is however an experimental one that does not coincide fully with a pure sample of diffraction events. In particular, a gap at the detector level can be masked by other interactions occurring during the same beam intersection in the CMS (pile-up). Also, an additional activity filling the gap can be generated by the underlying event present in the diffractive interaction or could come from electronic noises. On the other hand, not all gaps correspond to the exchange of the pomeron. Some of them can be produced as fluctuations in the final state of a non-diffractive event, and some correspond to the imperfections of the detector system which does not record particles with very low transverse momenta. Therefore, a good understanding of how a data sample selected at the detector level translates into a real sample of diffractive events is one of the most important elements of all CMS diffraction analyzes (the CMS detector does not provide sufficient kinematical coverage for detecting scattered beam protons involved in the diffractive interaction and therefore, the selection must be based on a large rapidity gap alone). Therefore, when analyzing diffraction in CMS, it was important to take advantage of the experience gained in the Forward Jets (Low-X QCD) group, especially related to HF detectors, which are the basic instruments to detect large rapidity gaps.

A sample of soft diffraction events is selected by requiring one (or more) gaps in the rapidity. In principle such a sample should be referred to as a minimum bias diffraction sample, as it also contains hard diffraction events (events where apart from the rapidity gap there are hard objects such as eg pairs of high transverse momentum jets). However, such events are several orders of magnitude less common than soft diffraction events and therefore are neglected. Monograph describes soft diffraction analysis, including events with single and double diffraction dissociation of protons. Cross sections for such events are calculated and compared to phenomenological models. Predictions agree with observations.

In the scope of the monograph, three hard diffraction analyzes are presented. These are: production of pairs of high transverse momenta jets together with a large rapidity gap, production of intermediate bosons together with a rapidity gap, production of high transverse jets with a rapidity gap observed in between (the jet-gap-jet topology). In the case of the first of the above analyzes, the presence of interactions with the pairs of jets produced diffractively was observed. There were also strong indications of diffraction occurrence in the production of intermediate bosons with a gap. However the most interesting results, come from the events with the jet-gap-jet topology. From the theoretical point of view, between such jets, a hard pomeron is exchanged, the description of which involves the BFKL equations. After selection cuts imposed, these events were compared to the Monte Carlo predictions. Only those predictions that take into account the exchange of a hard pomeron described in the BFKL regime are capable of following the experimental data. This result provides the strongest evidence so far for the emergence of the BFKL-like dynamics in the proton-proton collisions at the LHC.

**Exclusive production**

Chapter 6 presents the CMS experimental results on the central exclusive production (CEP). Events with CEP can be initiated by the pomeron-pomeron, photon-pomeron or photon-photon interactions. In the first two cases, these processes correspond to specific diffractive interactions with a well-defined final state. Examples of such interactions include exclusive photon pairs production and exclusive production of pairs of pions. The analyzes of both of these channels performed in the scope of the Exclusive Physics group, which I was the first convener, are presented in the monograph. In the first case (the exclusive production of photon pairs), there were no events found in the data. That is why only the upper limit for the cross section for the exclusive production of photon pairs could be set. This limit is comparable to the present theoretical limits. In the case of the exclusive production of pairs of pions, it was possible to reconstruct a large number of events. This made possible to calculate the cross section, and also allowed the search in the area of invariant mass above 1.5 GeV for glueball states decaying into pairs of pions. There were two structures in the mass spectrum observed (around 1.6 and 1.9 GeV), but due to the not trivial background modeling it was impossible to determine the significance of these observations. In the case of photon-photon interactions, an interaction is described by a pure QED calculations. Therefore, channels of exclusive production initiated by photon-photon interactions can be a very good test for LHC luminosity calculations, CMS detector performance and triggering system. Two analysis are described in the monograph - one with electron pairs and the other with muon pairs production in photon-photon interactions. The final analysis presented in the monograph is an analysis of the exclusive production of pairs of W bosons in photon-photon interactions. This analysis allowed to determine the strongest experimental limits on the anomalous quartic gauge coupling constant.

The extensive program of the Exclusive Physics group could not be implemented without an excellent knowledge of all the CMS detectors, including forward detectors, which allow to reject most non-exclusive events at early stages of the selection. In addition, exclusive studies require excellent detector stability over time and a large number of dedicated Monte Carlo samples. Minor fluctuations in the electronics noise level can lead to the rejection of exclusive events (electronics noise can be misidentified with additional particles). That is why it was important to supervise the detector behavior within the DQM group and the PVT group.

In 2014 a new CMS subdetector - Precision Proton Spectrometer (CT-PPS) was approved. This detector was included in the CMS system in 2016. It extends the CMS detection capabilities with the ability to reconstruct protons scattered in diffractive and exclusive interactions in the vicinity of the beam. With the CT-PPS, it is possible to carry out a variety of diffractive and exclusive analyzes, even in the case of a high pile-up present at high luminosity conditions. The goal is to detect the exclusive production of Higgs boson, and perhaps also supersymmetric particles.

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