Attachment no. 2b to the "Application for Initiation of habilitation procedure"
(file: Konecki_autopresentation.pdf)

Dr. Marcin Konecki
University of Warsaw, Faculty of Physics

Warsaw, December 30^{th}, 2014

Autopresentation

Summary of professional accomplishments

Contents

1 Personal data

First name and surname: Marcin Konecki

2 Diploma and scientific degrees

Doctor of Philosophy – University of Warsaw, 1998
Thesis title: *CP violating effects in B-meson decays with multi-muon final states – simulation study in the CMS detector*
Supervisor: Prof. Dr. Hab. Jan Królikowski
Reviewers: Prof. Dr. Hab. Danuta Kisielewska, Prof. Dr. Hab. Ewa Rondio

Master of Science – University of Warsaw, 1992
Thesis title (in Polish): *Badanie systemu wyzwalania detektora CMS przy Large Hadron Collider*
Supervisor: Prof. Dr. Hab. Jan Królikowski

3 Employment and scientific biography

3.1 Employment

Oct 2014 – present: Scientific Technician in the Institute of Experimental Physics, University of Warsaw

Oct 2004 – Sep 2014: Associate Professor (Polish adiunkt) in the Institute of Experimental Physics, University of Warsaw

Aug 2002 – Aug 2004: Post-doc at the University of Basel

May 2000 – Jul 2002: Research Fellow at CERN

Jul 1998 – May 2004: Associate Professor (Polish adiunkt) in the Institute of Experimental Physics, University of Warsaw (on leave of absence during May 2000 – May 2002)

Sep 1997 – Jun 1998: Technician in the Institute of Experimental Physics, University of Warsaw

3.2 Education

1992 – 1997: Ph. D. studies, Faculty of Physics, University of Warsaw

1987 – 1992: M. Sc. studies, Faculty of Physics, University of Warsaw.
Graduated *magna cum laude*

3.3 Awards

2014: Diploma Award for group instructor to the course "Fundamentals of Physics I", awarded by Dean of the Faculty of Physics, University of Warsaw

2013: Individual Second Prize for coordinating work of the CMS Warsaw Group, awarded by Rector of the University of Warsaw

2011: Group Prize for measurements validating the Standard Model in proton-proton collisions at the highest energies, awarded by Rector of the University of Warsaw

1998: Individual Prize for Ph. D. thesis of a great importance for the CMS experiment, awarded by Rector of the University of Warsaw

3.4 Participation in international conferences, workshops and courses

- "RPC2014: The XII Workshop on Resistive Plate Chambers and Related Detectors" (International Conference),
  23-28 Feb 2014, Department of Engineering Physics of Tsinghua University, Beijing, China,
  talk on behalf of the CMS collaboration:
  The RPC based trigger for the CMS experiment at the LHC

- "XXXIV-th IEEE-SPIE Joint Symposium Wilga 2014", Wilga, Poland,
  talk: *The Muon Trigger of the CMS experiment - Warsaw Group Activites*

- "Epiphany 2014: XX Cracow Epiphany Conference on the Physics at the LHC",
  8-10 Jan 2014, Cracow, Poland,
  talk on behalf of the CMS collaboration:
  CMS: Performance, Physics, Perspectives

- "XXX-th IEEE-SPIE Joint Symposium Wilga 2012", Wilga, Poland,
  talk: *The CMS performance in 2011 with an emphasize on Higgs searches*

- "Epiphany 2011: Cracow Epiphany Conference on the First Year of the LHC",
  10-12 Jan 2011, Institute of Nuclear Physics PAN, Cracow, Poland,
  talk on behalf of the CMS collaboration:
  CMS overall performance and physics results in 2010

- "EPS-HEP2009: The 2009 Europhysics Conference on High Energy Physics", (International Conference)
  16-22 Jul 2009, Cracow, Poland,
  talk on behalf of the CMS collaboration:
  Muon Reconstruction and Identification in CMS

- "XXIV-th Symposium Wilga 2009", Wilga, Poland,
  talk: *The RPC trigger for the CMS experiment at the LHC*

- "Vertex 2007: 16th International Workshop on Vertex detectors" (International Conference),
  23-28 Sep 2007, Lake Placid, NY, USA,
  talk on behalf of the CMS collaboration:
  Vertex reconstruction and tracking in the trigger algorithm for CMS

- "CMS Pixel Software Workshop", 11-15 Jan 2007, Johns Hopkins University, Baltimore, MA, USA,
  talks on pixel reconstruction and pixel data format conversion

- "Physics at LHC" (International Conference),
  3–8 Jul 2006, Cracow, Poland
  member of the Organizing Committee

- "EPS-HEP2003: European Physical Society International Europhysics Conference on High Energy Physics"
  17-23 Jul 2003, Aachen, Germany

- "BEAUTY 2003: The 9th International Conference on B-Physics at Hadron Machines", 14 - 18 Oct 2003 at Carnegie Mellon University, Pittsburgh, PA, USA,
  talk on behalf of the CMS collaboration:
  Online Event Selection at the CMS Experiment

- "4th CMS Pixel Workshop", 22-26 Oct 2002, CERN/PSI,
  talks on $H \to \tau\tau$ **and pixel seeding**

- "International Conference on CP Violation Physics"
  Sep 2000, Ferrara, Italy
  talk on behalf of ATLAS and CMS collaborations:
  Prospects for CP violation measurements with ATLAS and CMS

- "28th International Conference in High Energy Physics"
  Warsaw, Poland 1996

- "BEAUTY 94" (International Conference)
  Mont Saint-Michel, France 1994
  talk on behalf of CMS collaboration:
  A study of Control Channels for CP Violation

- "1993 European School of High-Energy Physics"
  Zakopane, Poland 1993

- "XVI Kazimierz Meeting on Elementary Particle Physics" (International Conference)
  Kazimierz Dolny, Poland 1993
  talk on behalf of CMS collaboration:
  CP violation studies with CMS

3.5 Additional information about the author's professional career

I have been working in the Compact Muon Solenoid (CMS) experiment since 1991. At that time the Warsaw Group has expressed its interest in participating in the trigger project of CMS [5][1] experiment for a planned, at that time, Large Hadron Collider (LHC) located at CERN laboratory in Geneva, Switzerland. I joined this effort from the beginning and this work has been continued until now and is related to various aspects of the muon trigger of CMS. My work on the muon project was accompanied by successful finalization of the CMS and LHC commissioning projects and followed by successful realization of the CMS physics program during the period of LHC Run-1 (2010–2013), including the discovery of Higgs boson [17]. The main fields and aspects of my work in high energy physics are summarized below. Traditionally, I divide my scientific biography in the period before and after obtaining Ph.D. However, my activities before Ph.D. extended beyond B-physics, which was the subject of my thesis.

Before obtaining Ph.D. My initial work concerned possibility to use Resistive Plate Chamber (RPC) detectors for fast muon triggering in the LHC environment. In years 1991–1992 I wrote a simplified simulation code of the CMS detector and its trigger system. At first it was a stand-alone simulation program, then implemented in a GEANT framework. These initial analyses are summarized in my M.Sc. thesis supervised by Prof. Jan Królikowski.

[1]See Section 3.6 for a list of publications important for my scientific career, also referenced here.

In 1991 I spent two months at DESY, Hamburg, Germany as a summer student. I was participating in development of software code for the ZEUS BAC Calorimeter, which aimed to verify GEANT description of the BAC test module.

In 1992, for a few months, I was involved in tests of the Warsaw RPC prototype chambers. I wrote a stand-alone software for data taking and control of the test-stand built in the CAMAC standard.

I continued to work on the design of RPC-based muon trigger and its algorithms until 2001. Since the algorithms are based on comparison of patterns, the RPC trigger is called also PACT (PAttern Comparator Trigger). During that period I was the person responsible for RPC trigger and RPC sub-detector simulation and analysis in the CMS simulation software frameworks. My analysis code was written initially in Fortran and then ported to C++. This work is summarized in [9,10,11]. I was also one of the main contributors and one of the editors of the RPC trigger section in CMS Level-1 Technical Design Report (TDR) [2] (Chapter 9).

Between 1993 and 1998 I have been actively participating in one CMS physics groups, which interests were focused on the B-physics. This work involved simulation of the processes contributing to CP-violation and various feasibility studies in the framework of CMS. The reconstruction of muons in the final state and triggering aspects were emphasized. Results of this work were presented in my Ph.D. thesis supervised by Prof. Jan Królikowski. The partial results of my studies were also included in the CMS Technical Proposal and are summarized in [25].

In the period of 1992–2000 I was also actively involved in managing a computer cluster of the High-Energy group at the University of Warsaw. The cluster consisted of computers with various hardware architectures, including SGI, Sun and PCs. At that time I was an administrator, promoter, and one of the first users of the Linux operating system inside the HEP group in Warsaw.

After obtaining Ph.D. In years 2000–2002 I was working as a Research Fellow at CERN within the muon PRS (Physics Reconstruction and Selection) group led by Prof. Paris Sphicas. I contributed significantly to the muon reconstruction algorithms for the CMS High-Level Trigger. My activities were mainly focused on estimating rates of combined muon-calorimetric triggers, and on development of the muon isolation algorithms. The isolation algorithms were based on the information from: calorimeters, simplified track reconstruction with the Pixel Detector and the full CMS track reconstruction. The results of these studies are summarized in the CMS Data Acquisition and High-Level Trigger TDR [3] (Chapters 15.3.2–15.3.4) and described in details in [15], and updated later by me in the CMS Physics TDR, Vol. I (Detector Performance and Software) [4](Chapter 9.3).

During my CERN fellowship I was also responsible for feasibility studies of triggering on a MSSM Higgs particle in the $A/H \rightarrow \tau\tau \rightarrow \mu + \tau_{\mathrm{JET}}$ (+X) channel. This work is presented in Chapter 15.5.9 of [3]. It marks involvement of the Warsaw group in the analysis of this channel and this activity still continues to date. I was also the co-supervisor of a Ph.D. thesis on that subject, written by one of the CMS Warsaw group members. The early studies of tau lepton reconstruction, to which I was contributing, are documented in [14].

Between year 2002 and 2004 I was working at the University of Basel in the group led by Prof. Ludwig Tauscher. This group, in collaboration with another group from Paul Scherrer Institute (PSI) contributed to the Pixel Detector project for the CMS experiment. The Pixel Detector is one of the key components of the CMS tracking system and provides a few high-precision measurements essential for track reconstruction. My contribution to the Pixel Detector project was also continued after finishing my contract with the University of Basel. At that time I also became the main person co-responsible for CMS track reconstruction code. Within that activity I developed a set of packages in the CMS software framework for simplified pixel-based track reconstruction. Its functionality included finding the hits compatible with a given track specification, construction of objects describing the found track candidates and assignment of track kinematics. Direct applications of the developed code included: fast reconstruction of the primary vertex, isolation algorithms, and - first of all - generation of seeds for full track reconstruction. This code is still partially maintained by me even at present and is used by the CMS experiment in online algorithms and in offline reconstruction. The above mentioned activities are summarized in [12] and became my important contribution to [4]. In addition, I participated in Pixel Detector beam tests [13]. I had also developed, and maintained (until 2010), software packages for converting of Pixel Detector data from raw detector format to the one used during event reconstruction. The PSI group invited me a few times for about month-long visits.

Since 2004 I have been working again at the University of Warsaw. I am responsible for large fraction of RPC trigger related activities. The list of tasks, to which I often provided a leading contribution, includes: system commissioning, operation and maintenance, RPC trigger data analysis, online and offline RPC and PACT data quality monitoring, RPC data format conversion from detector raw data to the format used in event reconstruction.

In addition, I am also participating in RPC trigger, RPC detector and global CMS shifts, taking care about system running. I was also a Level-1 trigger Detector on Call expert.

Since 2007 I am coordinating local CMS activities in Warsaw. Currently and I am a deputy of the Warsaw group leader in CMS. I was also a deputy leader of the RPC DPG (Detector Performance Group) during the period of CMS commissioning. I am also officially responsible for the Level-1 RPC-based trigger in the CMS experiment.

Presently my main activity is concentrated on the upgrade of the Level-1 CMS muon trigger [6] (i.e. new Muon Track Finder), in which the Warsaw group is designing a barrel-endcap overlap part (OMTF), covering pseudorapidity range of $0.8 < |\eta| < 1.25$ [7].

I presented my work on muon triggering and reconstruction, isolation, Pixel Detector reconstruction and physics results during numerous CMS internal meetings, prestigious CMS Weeks Meetings and several international conferences.

3.6 Selection of papers featuring scientific achievements

The full list of my publications, based on the Web of Science database, is given in Attachment no. 3. Taking into account large number of my publications, being a result of my long work in the CMS collaboration, in order to better characterize my contribution to the muon trigger of the CMS experiment, I selected the most relevant publications below. In addition, since the Web of Science database neither includes all the publications nor the internal reports issued be the CMS experiment, the list is supplemented with additional bibliography records. In particular the list is supplemented with selected reports documenting development of the CMS experiment and my conference reports.

For each item in the list I give a brief description of document and my involvement. When appropriate a position in the publication list in attachment no. 3 is marked, otherwise I compute my "calculated contribution" defined as the inverse of the number of authors of the document.

3.6.1 Selected CMS design reports

1 **CMS** Collaboration, *CMS: The Compact Muon Solenoid: Letter of intent for a general purpose detector at the LHC*", CERN/LHCC CERN-LHCC-92-03, CERN-LHCC-I-1, CERN, Geneva, 1992. Report prepared towards approval of the CMS experiment. The results of my early RPC trigger analyses are included.

2 **CMS** Collaboration, *CMS. The TriDAS project. Technical Design Report, Volume 1: The Trigger Systems*. CERN/LHCC 2000-038, CMS TDR 6.1 in Technical Design Report CMS. CERN, Geneva, 2000.

The main CMS report dedicated to Level-1 trigger. I am co-editor of the chapter describing RPC-based trigger, the author of trigger emulation software, and co-author of trigger studies

3 **CMS** Collaboration, *CMS. The TriDAS Project. Technical Design Report, Volume 2: Data Acquisition and High-Level Trigger*, CERN/LHCC 2002-026, CMS TDR 6.2 in Technical Design Report CMS. CERN, Geneva, 2002.
The main CMS report dedicated to HLT. My most important contribution is the study of muon isolation. I am also the author of feasibility studies of triggering in A/H$\rightarrow\tau\tau\rightarrow\mu + \tau_{\mathrm{JET}}$ + X channel. I gave also a contribution to muon reconstruction and analysis methods. This report is published and is included as Ref. 342 in Attachment no. 3.

4 **CMS** Collaboration, *CMS Physics: Technical Design Report Volume 1: Detector Performance and Software*. CERN-LHCC-2006-001, CMS-TDR-8-1 in Technical Design Report CMS. CERN, Geneva, 2006
The main CMS report dedicated to reconstruction methods. My most important contribution is the development of regional pixel-based track reconstruction, used also for track seeding. It includes also muon isolation chapter, written by me, which includes results of my studies.

5 **CMS** Collaboration, S. Chatrchyan *et al.*, *The CMS experiment at the CERN LHC*, JOURNAL OF INSTRUMENTATION, **3**, (AUG 2008).
The main reference for CMS detector descriptions. Ref. 350 in Attachment 3.

6 **CMS** Collaboration, *CMS Technical Design Report for the Level-1 Trigger Upgrade*. No. CERN-LHCC-2013-011. CMS-TDR-12 in Technical Design Report CMS. CERN, Geneva, 2013.
The report dedicated to trigger upgrades. Warsaw group is involved in design and construction of new system.

3.6.2 Selected documents related to muon trigger (PACT and OMTF)

7 W. M. Zabołotny, D. Bartkiewicz, M. Bluj, K. Buńkowski, A. Byszuk, K. Doroba, M. Górski, A. Kalinowski, K. Kierzkowski, M. Konecki, J. Królikowski, W. Okliński, M. Olszewski, and K. Poźniak, *FPGA Implementation of Overlap MTF Trigger - preliminary study*, Proc. of SPIE 9290 (2014).
Calculated contribution: 7%.
A first document describing OMTF. I am co-author of the OMTF concept and algorithm.

8 K. Buńkowski, K. Poźniak, M. Bluj, K. Doroba, M. Iskanius, A. Kalinowski, K. Kierzkowski, M. Konecki, J. Królikowski, I. Kudła, F. Loddo, W. Okliński, A. Ranieri, G. de Robertis, T. Tuuva, G. Wrochna, W. Zabołotny, *Synchronization methods for the PAC RPC trigger system in the CMS experiment*, MEASUREMENT SCIENCE & TECHNOLOGY, **18**, 8, (AUG 2007),
Ref. no. 353 in Attachment 3.
Summary of development of synchronization methods before the CMS startup.

9 G. Bruno and M. Konecki, *Simulation of the baseline RPC trigger system for CMS : Efficiency and Output Rates in Single Muon Topology*, CMS note CMS-NOTE-2001-012, CERN, Geneva, 2001
Calculated contribution: 50%
Note describing RPC trigger simulation studies. I am the author of emulator software and several tools used in the studies.

10 M. Andlinger, A. Kluge, F. Szoncso, G. Walzel, C.E. Wulz, P. Gorodenski, F. Klefenz, R. Manner, G. L. Bencze, A. Csilling, H. Czyrkowski, R. Dąbrowski, W. Dominik, M. Konecki, J. Królikowski,

M. Lewandowski, Z. Mazur, K. Sulowski, M. Górski, M. Szeptycka, M. DellaNegra, I. Kudła, M. Pimia, E. Radermacher, C. Seez, G. Wrochna, *Pattern Comparator Trigger (PACT) for the muon system of the CMS experiment*, NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS, **370**, 2-3, (FEB 21 1996),
Ref. no. 366 in Attachment 3.
Initial description of RPC trigger concept. Document signed by trigger group.

11 M. Konecki, J. Królikowski, G. Wrochna, *Simulation study if the RPC based, single muon trigger for CMS*, CMS technical note CMS-TN-1992-039, CERN, Geneva, 1992
Calculated contribution: 33%. I am the main author of presented trigger performance.

3.6.3 Selected documents related to algorithms of reconstruction

Works on pixel detector

12 S. Cucciarelli, M. Konecki, D. Kotlinski, and T. Todorov, *Track reconstruction, primary vertex finding and seed generation with the Pixel Detector*, CMS note CMS-NOTE-2006-026, CERN, Geneva, 2006
Calculated contribution: 25%
Main note describing stand-alone regional track and vertex reconstruction in the Pixel Detector. I gave leading contribution to development of track reconstruction algorithms in Pixel Detector (75%)

13 Y. Allkofer, C. Amsler, D. Bortoletto, V. Chiochia, L. Cremaldi, S. Cucciarelli, A. Dorokhov, C. Hoermann, R. Horisberger, D. Kim, M. Konecki, D. Kotlinski, K. Prokofiev, C. Regenfus, T. Rohe, D. A. Sanders, S. Son, M. Swartz, T. Speer, *Design and performance of the silicon sensors for the CMS barrel pixel detector*,
Ref. no. 349 in Attachment 3.

Reconstruction of tau

14 S. Gennai, F. Moortgat, L. Wendland, A. Nikitenko, S. Wakefield, G. Bagliesi, S. Dutta, A. Kalinowski, M. Konecki, D. Kotlinski, *Tau jet reconstruction and tagging with CMS*, EUROPEAN PHYSICAL JOURNAL C, **46**, (JUL 2006),
Summary of early studies of tau-jet reconstruction.
Ref. no. 355 in Attachment 3.

Muon isolation

15 N. Amapane, M. Fierro, and M. Konecki, *High Level Trigger Algorithms for Muon Isolation*, CMS note CMS-NOTE-2002-040, CERN, Geneva, 2002.
Calculated contribution: 33%
Main note describing development of muon isolation algorithms, included in HLT TDR. I gave the leading contribution to the algorithm development (60%)

3.6.4 Selected results of the CMS experiment

16 **CMS** Collaboration, S. Chatrchyan *et al.*, *Measurement of the* $B^0_s \to \mu^+\mu^-$ *branching fraction and search for* $B^0 \to \mu^+\mu^-$ *with the CMS experiment*, PHYSICAL REVIEW LETTERS, **111**, 10, (SEP 5 2013).

Ref. no. 78 in Attachment 3.
A very important measurement in B-physics.

17 **CMS** Collaboration, S. Chatrchyan *et al.*, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, PHYSICS LETTERS B, **716**, 1, (SEP 17 2012),
Ref. no. 182 in Attachment 3.
One of the most important publications so far, referring the discovery of the Higgs boson

18 **CMS** Collaboration, S. Chatrchyan *et al.*, *Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at root s=0.9 and 2.36 TeV*, JOURNAL OF HIGH ENERGY PHYSICS, 2, (FEB 2010).
Ref. no. 344 in Attachment 3.
One of the first CMS physics analyses with data (first publication). Is is particularly relying on pixel-tracks.

3.6.5 Conference reports

19 M. Konecki, *The RPC based trigger for the CMS experiment at the LHC*, JOURNAL OF INSTRUMENTATION, **9**, (JUL 2014), The XII workshop on Resistive Plate Chambers and Related Detectors.
Ref. no. 18 in Attachment 3.
Conference report, on behalf of the CMS collaboration.
The results of my work are included and emphasized.

20 M. Konecki, *CMS: Performance, Physics, Perspectives*, ACTA PHYSICA POLONICA B, **45**, 7, (JUL 2014), 20th Cracow Epiphany Conference on the Physics at the LHC.
Ref. no. 17 in Attachment 3.
Conference report, on behalf of the CMS collaboration.
The review of the most important physics results of the CMS experiment in LHC Run-1.

21 M. Konecki, *CMS overall performance and physics results in 2010*, ACTA PHYSICA POLONICA B, **42**, 7, (JUL 2011), Cracow Epiphany Conference on the First Year of the LHC.
Ref. no. 279 in Attachment 3.
Conference report, on behalf of the CMS collaboration. The review of most important CMS physics results.

22 M. Konecki, *Muon reconstruction and identification in CMS*, PoS EPS-HEP2009 (2009) 131.
Calculated contribution: 100%.
Conference report, on behalf of the CMS collaboration. The results of my work are included and emphasized.

23 M. Konecki, *Vertex reconstruction and tracking in the trigger algorithm for CMS*, PoS VERTEX2007 (2007) 033.
Calculated contribution: 100%.
Conference report, on behalf of the CMS collaboration. The results of my work are included and emphasized.

24 M. Konecki, *Online event selection at the CMS experiment*, AIP Conf.Proc. 722 (2004) 207–213.
Calculated contribution: 100%.
Conference report, on behalf of the CMS collaboration. The results of my work are included and emphasized.

25 M. Konecki, *Prospects for CP violation measurements with ATLAS and CMS*, NUCLEAR PHYSICS B-PROCEEDINGS SUPPLEMENTS, **99B**, (MAY 2001), International Conference on CP Violation Physics.
Ref. no. 363 in Attachment 3.
Conference report, on behalf of the CMS collaboration. The results of my work are included and emphasized.

4 Presentation of achievement (in accordance with Polish regulation Art. 16 ust. 2 Ustawy z dnia 14 marca 2003 roku „O stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki" (Dz.U. nr 65 poz. 595 z późniejszymi zmianami))

As the scientific achievement I present a monograph entitled:

The Muon Trigger of the CMS experiment – design, performance, upgrade.

author: Marcin Konecki
published by the University of Warsaw Publishing, Warsaw, 2014,
ISBN 978-83-235-1670-5.

This monograph presents the muon trigger of the Compact Muon Solenoid (CMS) experiment. The long and very active work in the muon trigger group, participation in system design, operation and upgrade efforts, motivated me to emphasize that in the title of the presented monograph. The monograph also overviews the main CMS physics results, including those to which I was contributing, and which particularly use the software reconstruction tools developed by me.

The monograph is organized in chapters. In the first chapter the CMS detector is presented. Its operation and early performance results are discussed. In the second chapter the CMS Level-1 trigger system is overviewed with the emphasis on the muon part. The trigger performance results are also shown. The High-Level Trigger (HLT) is discussed in the third chapter. The muon and track reconstruction methods are presented, their performance is analyzed. The fourth chapter is dedicated to CMS physics results. It includes the discovery of the Higgs boson and selection of other measurements. The perspectives for CMS upgrade are discussed in the last chapter. There are three appendices to the monograph presenting various aspects of event reconstruction to which my contribution was particularly prominent, and a glossary of acronyms. In the first appendix the performance of the RPC trigger is discussed. A review of simplified reconstruction techniques with the Pixel Detector, also used for seeding and relevant to Chapter 3, is given in the second appendix. The muon isolation studies are included in the third appendix.

This monograph is based on the revised conference reports given by me on behalf of the CMS collaboration, my contribution to CMS TDRs and on the selected CMS notes to which I gave leading contributions. Each chapter is preceded by a short information about my contribution to the subject discussed in a given chapter. The summary of main topics discussed in each chapter is given below.

Chapter 1: The CMS experiment at the LHC – design and initial performance

The CMS experiment is one of general purpose experiments at the LHC. Among the CMS design guidelines a very good muon reconstruction quality is in the first place. The large CMS solenoid encloses the tracker system and calorimeters. Outside of the solenoid the muon system is located. The barrel part of the detector, made of detectors oriented roughly parallel to the beam line, is supplemented with two endcaps which improves detector hermeticity. The muon system consists of 3 types of detectors interlaced with iron return yoke – Drift Tubes (DT) placed in the barrel, Cathode Strip Chambers (CSC) in the endcaps and Resistive Plate Chambers (RPC) in both barrel and endcaps. The pseudorapidity (η) coverage of the muon system extends up to $|\eta| \approx 2.4$. During the Run-1 (2010–2013) the LHC has been operated smoothly, delivering in its main proton-proton collision mode the statistics corresponding to about $30\,\text{fb}^{-1}$ in the CMS detector. This data were recorded and then validated by the CMS collaboration with high efficiency in each step, reaching or even exceeding 90%. The total integrated luminosity of $5.1\,\text{fb}^{-1}$ at $\sqrt{s}$ =7 TeV recorded in years 2010–2011 and $19.7\,\text{fb}^{-1}$ at $\sqrt{s}$ =8 TeV recorded in 2012 was used for data analysis in most paramount analyses.

The CMS collaboration has adopted a two step triggering system. The first step (Level-1) trigger is responsible for the reduction of nominal 40 MHz LHC bunch-crossing input rate down to 100 kHz. The Level-1 is based on custom, partially programmable hardware devices. The rate reduction is achieved using coarse data from calorimeters and muon system, but not from the tracker. During the Level-1 signal processing the detector data is temporarily stored in detector pipe-lines and, then, readout upon the Level-1 accept signal. The information from sub-detectors are further processed at the HLT. The HLT algorithms are executed at a computer farm, reconstructing online the events using full-granularity data from all the CMS sub-detectors, including the tracker. The set of algorithms and cuts used by the trigger is called the (Level-1 or HLT) trigger menu. The events selected by the HLT are grouped in streams. Those intended for physics analyses are recorded with a rate of about 1 kHz, and are further grouped into data dedicated for the main physics program or into supplementary data for additional analyses, for which an offline reconstruction can be delayed.

The CMS detector was initially commissioned with test beams data and cosmic runs before the LHC start-up. The commissioning has been continued with early LHC data. The key aspects were: calibration and alignment of sub-detectors, validation of reconstruction algorithms, comparison of detector response (reconstructed physics objects) with predictions of the simulation, validation and tuning of trigger algorithms and menus. The successful preparedness of sub-detectors has been demonstrated by measuring well known physics processes. A good illustration of tracking performance can be, for example, the reconstruction of baryons cascaded decays which rely on track reconstruction quality as well as on primary and secondary vertex finding techniques. A typical example of good muon reconstruction is visible in the measured di-muon invariant mass distribution with well distinguished structure of the Υ family. The precise measurement of electromagnetic cascades and jets are another vital aspect of reconstruction in CMS. The CMS collaboration has developed several methods for calibration of the calorimeters. A good illustration of calorimeter performance is the measured $Z \rightarrow e^+e^-$ invariant mass shape as well as jet p_T spectra. Among several reconstruction methods developed by CMS one of the most important is the particle flow technique. It attempts to identify and individually reconstruct all the particles produced in collisions using information from all CMS sub-detectors.

Chapter 2: The Level-1 muon trigger. Performance

The Level-1 trigger is organized hierarchically. The calorimeter trigger is composed of Regional Calorimeter Trigger (RCT) and Global Calorimeter Trigger (GCT). The input calorimeter data is organized in Trigger Primitives build of energy deposits in calorimeter towers. At the RCT the electron/photons candidates as well as jet and tau constituents are reconstructed locally. The RCT information is combined at the GCT, where all trigger objects are finally build, including supplementary information, such as, total scalar and vector energy sums and missing energy.

The muon trigger consists of: DT Track Finder trigger (DTTF) – reconstructing muon candidates based on data from DT, CSC Track Finder (CSCTF) trigger – using CSC data and PACT (PAttern

Comparator Trigger) – based on RPC data. The PACT is also called RPC Trigger. In case of DTTF and CSCTF the input data are organized in segments, which are built of muon hits in one chamber by DT and CSC local triggers. In case of RPC there is no multi-layer chamber geometry, thus RPC hits are direct input to PACT algorithm.

In case of DTTF the segments are extrapolated between various chambers using local segment position and local segment bending angle within a chamber. The matched segments form the muon candidates. The muon momentum and sign of its charge are defined by position of two available inner-most segments and are assigned by means of look-up tables. The CSCTF tracks are build in a similar way. The muon momentum measurements is based on memory look-up tables addressed by segment pseudorapidity position and azimuthal angle difference between up to 3 segments contributing to a muon candidate. The PACT first selects hits from a part of the detector. The pattern of RPC hits appearing in a given event is compared with a set of pre-defined patterns implemented in programmable electronic circuit. The pre-defined patterns are obtained from large statistics Monte Carlo simulations and have the assigned p_{T}-code, and charge sign. The minimal number of hits in coincidence needed to form a valid pattern is 3. The PACT also implements a special trigger intended to search for Heavy Stable Charged Particles (HSCP) predicted by some supersymmetry models, having event signatures similar to prompt muons, but characterized by signals delayed in time. For each muon sub-trigger the reconstructed muon candidates have assigned quality of reconstruction bits, based on the number and topology of layers contributing to the measurement. The DTTF, CSCTF and PACT muon candidates are collected by the Global Muon Trigger (GMT). The GMT merges and sorts candidates using their transverse momentum and quality.

The muons selected by the GMT and the calorimeter objects provided by GCT, supplemented by some CMS Technical Triggers are sent to the Global Trigger. In the Global Trigger the Level-1 decision to reject the event or to send it to HLT for further selection is taken. This decision is based on event topology, kinematics, energy sums, muon quality and additional information provided by technical triggers. The thresholds applied by Level-1 in late 2012, for single muon transverse momentum selection were 16 GeV/c in full η range and 12 GeV/c in $|\eta| < 2.1$. The single electron/photon transverse energy thresholds were 20 GeV and 18 GeV for isolated candidates.

The performance of the muon trigger is expressed in terms of its efficiency and rate. A good timing performance is also mandatory. The efficiency is measured with a tag-and-probe method, which allows one to measure trigger efficiency with no bias due to event selection and reconstruction. It is based on di-muon decays of resonances, typically Z of J/ψ particles. In such events one of the muons is triggering the event, while the efficiency is measured for the second one, identified by means of an invariant mass constraint. The GMT turn-on curves as function of muon p_{T} have the efficiency plateau at approximately 95%, which does not decrease with increasing trigger threshold on muon p_{T}. In order to measure the trigger rates a special CMS data stream is used. It includes only trigger candidates thus its data volume is reduced. The single muon rate can be controlled by p_{T}-threshold for thresholds below 20 GeV/c. Above that value the rate curve starts to saturate due to low-p_{T} muons mis-reconstructed as high-p_{T} ones, which is not a desired feature. This effect is especially important for pseudorapidity regions $|\eta| > 2.1$. The studies of timing performance of the Level-1 trigger allows one to conclude that the trigger impurities due to event assignment to wrong LHC bunch-crossing is at the per-mill level.

Chapter 3: The Muon track reconstruction at the High-Level Trigger

The computer farm executing the HLT algorithms was evolving during LHC Run-1 period, allowing to extend average event processing time following the increase of accelerator luminosity. The HLT algorithms are organized in modules, called paths. Each path is a sequence of reconstruction and filtering steps. Whenever possible, within a given path, the faster and less complex steps are executed prior to more advanced and detailed ones. Thus, the calorimeter and muon reconstruction always precede the tracker one. The trigger transverse momentum threshold applied by the HLT for a single muon reconstruction in late 2012 was 40 GeV/c, while in the case of isolated muon candidates it was lowered to 24 GeV/c.

The muon track in CMS can be measured by both, the muon system, outside the coil, and the silicon tracker. Their results can be combined. The reconstruction provided by the tracker is more precise with exception of very energetic muons. Thus the tracker determines muon momentum resolution for transverse momenta below $\sim$ 100 GeV/c. The muon and track reconstruction at the HLT is very similar to the offline case and differs mainly in configuration. It is based on the Combinatorial Track Finder (CTF) which combines the seeding step, pattern recognition and final fitting. In addition, an especially important at the HLT – selection step, can stop track reconstruction based on quality cuts and thresholds. This allows to reject some tracks quickly, but also to keep tracks reconstructed partially, when full precision is not mandatory.

The seeding step is very important at the HLT. The particularly desired feature is seeding purity. The CMS seeding is supported by stand-alone track and vertex reconstruction in the Pixel Detector which provides very precise position measurement. The seeds can be reconstructed only in predefined detector areas with constraints imposed on track direction, momentum and vertex, what allows for regional tracking. The seeds are based on hit-pairs and hit-triplets that are compatible with a desired track kinematics. The track finding is performed in iterative way to optimize the timing of reconstruction. In this approach the easy-to-reconstruct tracks are found first. Then, in order to find tracks more difficult to reconstruct, the hits assigned to previously reconstructed tracks are removed and the track finding is repeated, with less strict constraints on seeding.

The muon reconstruction at the HLT is done in steps. At first the muon is reconstructed based on muon system only. The result of this reconstruction is called a stand-alone muon. It is done in virtual Level-2 triggering step executed at the HLT. The reconstruction which involves tracker data is done in virtual Level-3 step. The result is called a Level-3 muon which may fall in one of 2 categories: a global muon – which combines results of reconstruction in the muon system and in the tracker, or a tracker muon – with a track reconstructed in the tracker only and matching a compatible deposit in the muon system. Each of Level-3 muon types uses different type of seeding. The muon reconstructions at Level-2 and Level-3 are based on the same CTF mechanism.

The isolation is a powerful selection criterion which is used in muon reconstruction at the HLT. It allows one to distinguish the potentially most interesting muons from single heavy objects decays from muons in QCD jets. The muon isolation is based on a single discriminant variable which takes into account the sum of transverse momenta of all tracks and the sum of calorimeter energies deposited around a muon candidate. The energy deposits are corrected for the pile-up effects by extracting the average energy deposit per event.

Chapter 4: Selected Physics results

The CMS experiment has a very rich physics program. The discovery of a new boson, identified as the Standard Model Higgs boson, is the most important CMS result, to date. CMS is investigating several Higgs decaying channels which also probe different production mechanisms. Within that, the Higgs decaying to pair of photon and pairs of electron/positrons or muons (4 leptons) via Z's are the most important channels. They are so called golden channel, used as performance benchmarks during CMS experiment design.

The $H \rightarrow \gamma\gamma$ channel is characterized by two energetic, isolated photons. The background arises mainly from QCD prompt photon production and misidentification of hadronic jet as photons. It is however successfully suppressed by excellent photon reconstruction and mass resolution. The $H \rightarrow$

ZZ $\rightarrow 4\ell$ channel require a low-statistic analysis. The main background is formed by non-resonant ZZ or $Z\gamma^*$ production. The analysis relies on the reconstruction of isolated electrons and muons, which must be reconstructed efficiently with very selective identification and optimized isolation methods, taking into account possible bremsstrahlung and final-state radiations. The mass of the Higgs boson measured in $\gamma\gamma$ and 4 lepton channels is $m_{\rm H} = 125.03^{+0.29}_{-0.31}\,{\rm GeV/c^2}$. Among other Higgs boson decay channels the $\rm H{\rightarrow}\tau\tau$ is interesting and important channel to study Higgs boson properties. The number of final state signatures involves reconstruction of muons, electrons but also narrow hadronic jets induced by tau hadronic decays. The decay involves neutrinos in the final state so the invariant mass cannot be determined precisely. The main source of background comes from $\rm Z{\rightarrow}\tau\tau$ decays which are studied by embedding methods. The combined from all analyses signal strength modifier parameter for the Higgs boson production is 1.00 ± 0.13. The analysis of the Higgs boson properties also confirms couplings and spin-parity values as predicted by the Standard Model.

The CMS collaboration has a rich program of precise measurements and tests of the Standard Model, including W, Z, top quark and jet measurements and heavy-ion studies. The current results do not show any deviations from predictions of the Standard Model. Among many measurements performed by CMS, the analysis of charged particle multiplicities and momentum spectra as well as topological correlations in two-particle distributions particularly depend on reconstruction of pixel-tracks within a Pixel Detector. Another important analysis done by CMS is a measurement of branching ratio of $\rm B_s \rightarrow \mu^+\mu^-$ decay. In addition a limit had been set on $\rm B \rightarrow \mu^+\mu^-$ decay. The wide range of searches for signs of supersymmetry and other exotic models has been performed but no signals of physics beyond the Standard Model have been found so far.

Chapter 5: Perspective outlook and Summary

In the next working period of the LHC, starting in 2015, the accelerator energy is expected to reach energy value close to its design parameters, while the luminosity should event exceed them. The upgrades of the accelerator will be accompanied by necessary improvements in the CMS apparatus. One of the major modernizations foreseen at CMS is replacing the current Pixel Detector with a new one. A performance degradation, which the current detector will inevitably suffer with luminosity increase, is the main motivation for this upgrade. The new detector will have better readout capabilities. To further improve pixel-based reconstruction and seeding also the number of layers will be increased, to provide 4 measurements.

Another major upgrade of CMS is the improvement of trigger purity at Level-1. This will be achieved by rebuilding the system. The muon trigger will also undergo major changes to its logic. Currently the trigger response is generated independently by three muon sub-triggers and separate trigger candidates are later combined by the GMT. Within the new trigger (called the Muon Track Finder) all sub-detector signals will be delivered to a single data-processing unit and the resulting muon candidate will take into account all the available information.

All of the above modifications are done in the context of further studies of electoweak symmetry breaking, tests of the Standard Model and searches of New Physics.