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Simon Spannagel

CMS Pixel Detector Upgrade and Top Quark Pole Mass Determination

Doctoral Thesis accepted by
the University of Hamburg, Germany

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Supervisor's Foreword

Particle physics aims to understand matter and forces at the fundamental level. Today's knowledge of the basic constituents of matter, the elementary particles, and their interactions is described in the standard model. The heaviest known particle is the top quark which was discovered in 1995 at the Tevatron Collider in the USA. Since 2011, it is produced and explored at the Large Hadron Collider (LHC) at CERN.

One of the large detectors at the LHC is the Compact Muon Solenoid (CMS) experiment. The detector records the products of the collision of protons in order to probe the standard model and to detect new, yet unknown particles and phenomena. Such modern experiments are state-of-the-art devices, and their design and conception require a deep understanding of the underlying physics and technologies as well as interdisciplinary cooperation. The thesis of Simon Spannagel provides major contributions to the design and tests of the detector on the one hand and the analysis of the collision data on the other hand.

The innermost part of the CMS experiment consists of about 65 million small sensitive pixels. It provides information about the trajectories of charged particles as close as possible to the collision point they originate from and thus enables the reconstruction of secondary decays. Since the start of the LHC operation in 2010, the CMS pixel detector performed extremely well. However, the luminosity provided by the LHC will surpass the design value by at least a factor of two in the next years exceeding the capabilities of this detector. In order to be able to fully exploit the physics potential of the increased collision rate, the pixel detector has to be replaced by a new and improved device. Simon Spannagel has delivered key contributions to the development and tests of this new detector. In his thesis, he describes systematic studies regarding the characterization of prototype detectors with the new pixel readout chip at the DESY test beam and the tools and techniques he developed for this purpose. The systematic studies of charge collection and resolution of the new detector are extremely precise and will serve as reference for future studies of the detector's performance. Moreover, Simon Spannagel describes a novel idea to use the so-called cluster skewness in order to improve the sensor resolution beyond the values reached so far.

The second part of Dr. Spannagel's thesis is related to top quark physics and based on the analysis of data collected by the CMS detector at a center-of-mass energy of 8 TeV. Due to its high mass, the top quark plays an important role in precision calculations of the standard model as well as in searches for new phenomena. The top quark does not form bound hadron states and thus allows studies of the bare quark properties and of quantum chromodynamics, which describes the interactions of quarks and gluons through the strong force. However, the top quark decay time is extremely short and it carries color charge which complicates the measurement of the mass. The relation between the experimentally reconstructed value and the top mass as a free parameter of the standard model is highly complex and theoretically uncertain.

For this reason, it is highly interesting that Simon Spannagel uses a method based on the analysis of differential cross sections. This method, applied for the first time on CMS data, is complementary to the standard measurement based on the kinematic reconstruction of the decay products. It allows accessing the top quark pole mass in a more direct way and with less theoretical uncertainties related to the interpretation of the measured value. The top quark mass obtained by Simon Spannagel has a larger experimental uncertainty compared to the CMS measurements from direct reconstruction. His approach, however, is very promising for the future when due to the higher luminosity of the LHC top quarks will be produced with much higher statistics and theoretical uncertainties will dominate. Thus, he shows a way how the top quark pole mass can be precisely determined in future.

In the thesis of Simon Spannagel new, innovative ideas are discussed related to the fields of modern silicon detectors and top quark physics. The contributions he made to the CMS experiment in both fields are highly relevant and of extraordinary scientific diversity and quality.

Hamburg, Germany
April 2017

Prof. Dr. Joachim Mnich

Abstract

In this dissertation, two different topics are addressed which are vital for the realization of modern high-energy physics experiments: detector development and data analysis. The first part focuses on the development and characterization of silicon pixel detectors. To account for the expected increase in luminosity of the LHC, the pixel detector of the CMS experiment will be replaced by an upgraded detector with new front-end electronics. Comprehensive test beam studies are presented which have been conducted to verify the design and to quantify the performance of the new front end in terms of tracking efficiency and spatial resolution. The tracking efficiency has been determined to be $99.7^{+0.3}_{-0.5}\%$, while the spatial resolution has been measured to be $(4.80 \pm 0.29)\ \mu\mathrm{m}$ and $(7.99 \pm 0.23)\ \mu\mathrm{m}$ along the $100\ \mu\mathrm{m}$ and $150\ \mu\mathrm{m}$ pixel pitch, respectively. Furthermore, a new cluster interpolation method is proposed which utilizes the third central moment of the cluster charge distribution and achieves improvements of the position resolution of up to 40% over the conventional COG algorithm. In the second part of the thesis, an alternative measurement of the top quark mass is presented. The mass is measured from the normalized differential production cross sections of dileptonic top quark pair events with an additional jet. The measurement is performed on data recorded by the CMS experiment at $\sqrt{s} = 8\,\mathrm{TeV}$, corresponding to an integrated luminosity of $19.7\ \mathrm{fb}^{-1}$. Using theoretical predictions at NLO in perturbative QCD, the top quark pole mass is measured to be $m_{\mathrm{t}}^{\mathrm{pole}} = 168.2^{+4.7}_{-2.1}\,\mathrm{GeV}$ with a precision of about 2.0%. The measurement is in agreement with other measurements of the top quark pole mass within the assigned uncertainties.

Preface

Already in the thirteenth century, ideas were developed on how science could potentially evolve in the future. The idea of the ARBOR SCIENTIÆ [1], or *tree of science*, forecasted a branching into different disciplines—a prediction which eventually became true after the last great polymaths of the renaissance. Instead of covering many different subjects, experts deepened the understanding of their specific fields to a level, where no single person could internalize all knowledge available. Over the centuries, these branches have undergone further ramification, and modern science comprises millions of leaves of different disciplines. However, in today's diverse scientific landscape, this foliage has become so dense that none of these subjects can be treated independently of the others and their differentiation becomes more and more difficult.

High-energy particle physics is no exception to this. The main goal of high-energy physics is the understanding of fundamental processes in nature, and its primary tool to explore the microcosm of the elementary constituents of matter is particle collisions. Elementary or composite particles are accelerated and brought to collision in order to produce new and unknown constituents, or to quantify known processes or parameters of a theory. The underlying theoretical framework for modern high-energy particle physics is the so-called standard model (SM), which represents the current state of knowledge and summarizes all known particles and interactions. Since its first formulation in 1961 [2], it has been constantly refined throughout the latter half of the twentieth century and by now provides high-precision predictions for many phenomena measured in nature.

The first particle accelerators have been built in the early 1930s [3–5], and since then, the collision energy has constantly been increased in order to probe new regimes and to challenge the predictions provided by the SM. With the requirement for higher collision energies, both the particle accelerators and the detectors have grown larger and larger over the past decades, and now constitute the largest and most complex machines ever built. Designing and conducting such an experiment requires detailed understanding of all physics and technology involved—from the working principles of the basic detector building blocks, to data acquisition, particle identification, and reconstruction, and finally to the measurements of the physics processes under investigation. This global and interdisciplinary endeavor would not be possible without the expert knowledge from many different fields of science such as cryogenics, solid state physics, material science, microelectronics, or high-performance computing.

The currently largest particle accelerator is the Large Hadron Collider (LHC), located at CERN near Geneva, Switzerland, which accelerates hadrons along its 27-km ring and brings them to collision at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$.[1] One of the experiments recording these collisions is the Compact Muon Solenoid (CMS) experiment, a 14,000 t general purpose particle detector with a length and diameter of about 22 and 15 m, respectively. It is one of the two experiments to discover the Higgs boson [6, 7], paving the path for the 2013 Nobel Prize in physics [8]. However, many questions are still waiting to be answered, and both the accelerator and the experiments are undergoing constant changes and improvements in order to push the boundaries of human knowledge.

The work presented in this thesis provides an insight into the diversity of problems to be solved in order to successfully conduct a high-energy physics experiment and is thus devoted to two different parts. After a general introduction to the field of particle physics in Chap. 1 and to the CMS experiment in Chap. 2, Part I describes the endeavor of designing, constructing, and commissioning a new pixel detector for CMS. Part II presents a measurement of the top quark mass from data recorded by the CMS experiment at $\sqrt{s} = 8\mathrm{TeV}$.

The CMS pixel detector is a hybrid silicon pixel-tracking detector and constitutes the innermost component of the CMS experiment. It provides spatial information about the path of charged particles with high resolution and hence is a crucial part of the experiment for the reconstruction of particle trajectories and for the identification of secondary decay vertices. The current CMS pixel detector has been designed for an instantaneous luminosity of $\mathcal{L} = 1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and performs well under these operation conditions. However, the luminosity provided by the LHC will exceed the design value by a factor of two or more within the next years, and the present pixel detector would be subject to severe inefficiencies arising from dead time and limited buffering capabilities of the front-end electronics. Thus, the CMS collaboration has decided to replace the pixel detector with a new device, which represents an advancement of the current design including a new readout chip (ROC). The new detector is currently being built by a collaboration of many institutes, and the replacement of the present detector is foreseen for the year-end technical stop of the LHC in 2016/17. The new front-end electronics also require a new data acquisition (DAQ) framework for laboratory tests and operation of prototypes, which has been implemented as part of this thesis and is in use by the entire CMS Pixel Collaboration for the quality control and calibration of detector modules.

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[1] Natural units are used throughout this thesis, with $c = \hbar = 1$. Consequently, energy, mass, and momentum are given in units of electron volts (eV). Electric charge is expressed in units of the elementary charge e.

In this thesis, test beam measurements for the characterization and design verification of the new ROC are presented. Test beams are beams of ionizing radiation which allow to assess the characteristics of particle detectors, and provide the opportunity to operate the devices in conditions close to the final deployment situation in the experiment, i.e., with external trigger signals and in synchronization with other detectors. The measurements have been performed at the DESY test beam facility using a reference detector for tracking which allows to predict the particle impact position in the so-called device under test with micrometer resolution. Precision measurements of the spatial resolution and tracking efficiency of the new ROC are presented and compared to detailed simulations of the charge deposition and collection in the silicon sensor material. Furthermore, the charge distribution among the different pixels of a cluster is studied in detail, and a new method for the determination of the track impact position based on the third central moment of the charge distribution is proposed.

The first part is structured as follows. An introduction to semiconductor tracking detectors is given in Chap. 3, followed by a description of the Phase I pixel detector for the CMS experiment in Chap. 4. Chapters 5 and 6 provide information about the simulation of CMS pixel detector modules using the PIXELAV software and about the pxarCore DAQ framework, respectively. Chapter 7 describes the DESY test beam facility as well as the experimental setup for the test beam qualification of the ROC. The analysis strategy and results of the test beam measurements are discussed in Chap. 8. Finally, Chap. 9 presents a new algorithm for the improvement of the spatial resolution of pixel detectors using the charge distribution within clusters.

The second topic of this thesis studies the heaviest known particle of the SM, namely the top quark. It has only been discovered in 1995 at the Tevatron accelerator [9, 10], and to this day, only the Tevatron and the LHC have reached the collision energy necessary to produce top quarks. At a collision energy of $\sqrt{s} = 8$ TeV, the inclusive cross section for the production of top quark pairs ($\mathrm{t\bar{t}}$) is about $\sigma = 245\,\mathrm{pb}$, and therefore, about five million $\mathrm{t\bar{t}}$ events have been produced at the LHC in the $19.7\,\mathrm{fb}^{-1}$ of data recorded in 2012. Owing to its high mass, the top quark has large implications for various parameters of the SM and allows detailed tests of quantum chromodynamics (QCD). The top quark does not form bound hadron states but predominantly decays directly to a bottom quark and a W boson, and thus allows to study the properties of a bare quark. Moreover, top quarks play an important role in searches for possible physics beyond the SM.

The top quark mass is usually either measured directly by reconstructing the event topology from its decay products and inferring the mass from this kinematic reconstruction, or via the mass dependency of the inclusive $\mathrm{t\bar{t}}$ production cross section. The currently most precise combination of direct measurements performed by the CMS collaboration yields a mass of $m_\mathrm{t} = 172.44 \pm 0.13(\mathrm{stat}) \pm 0.41(\mathrm{syst})$ GeV [11] with a relative uncertainty below 0.3%. However, the kinematic approach does not allow for the determination of a theoretically well-defined Lagrangian parameter in terms of perturbative QCD which can be related to the top quark mass. On the other hand, measurements from the cross section do not provide the same experimental precision but allow for the measurement of a well-defined mass parameter.

In this thesis, an alternative measurement is presented, which determines the top quark mass from differential cross sections using a global χ^2 template fit method. The differential cross section is determined from dileptonic $\mathrm{t\bar{t}}$ events, where both W bosons decay into lepton–antineutrino pairs, and which contain additional jet activity ($\mathrm{t\bar{t}}$ + jet). The observable ρ_S is proposed in [12] and is defined as the inverse of the invariant mass of the $\mathrm{t\bar{t}}$ + jet system. The mass is determined by comparing the differential cross section as a function of ρ_S to theoretical predictions with different top quark mass hypotheses. The measurement is performed both at the level of reconstructed particles from the detector response and after correction for detector acceptance, resolution, and efficiency. This allows to compare the sensitivity and the influence of different sources of systematic uncertainty on the methods. The theoretically well-defined pole mass of the top quark is measured using calculations of the $\mathrm{t\bar{t}}$ + jet matrix element at next-to-leading order (NLO) precision [13] with subsequent parton showering.

The second part of the thesis is organized as follows. After a brief introduction of physics with top quarks in Chap. 10, the simulation of collision events with the Monte Carlo (MC) method is presented in Chap. 11. The analysis strategy and event selection are described in Chap. 12, and the sources of systematic uncertainty relevant for the measurement presented are discussed in Chap. 13. The global χ^2 template fit method and the measurement of the top quark mass from the normalized ρ_S event distributions are presented in Chap. 14. Chapter 15 describes the unfolding of the distributions to generator level, the measurement of the normalized differential $\mathrm{t\bar{t}}$ + jet cross section, and the determination of the top quark mass and top quark pole mass from different theoretical predictions.

Finally, the findings of both parts of the thesis are summarized and a brief outlook on possible improvements of the analyses and additional measurements is given in the Summary and Prospects chapter.

Hamburg, Germany Dr. Simon Spannagel

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H. Jansen et al., “Performance of the EUDET-type beam telescopes”, *EPJ Tech. Instrum.* **3** (2016), no. 1, 7, 10.1140/epjti/s40485-016-0033-2, arXiv:1603.09669.

S. Spannagel, “Status of the CMS Phase I Pixel Detector Upgrade”, *Nucl. Instr. Meth. Phys. A* (2016) doi:10.1016/j.nima.2016.03.028, arXiv:1511.06084.

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Acronyms

ADC	Analog-to-digital converter, 22, 44, 58, 62, 72, 77, 99, 113, 118, 145
API	Application programming interface, 78
ATLAS	A Toroidal LHC Apparatus, 2, 20, 25, 167, 227
BC	Bunch crossing, 60
BORE	Begin-of-run event, 101, 103, 104
CCE	Charge collection efficiency, 43, 59
CDS	Correlated double sampling, 94
CERN	European Organization for Nuclear Research, 17
CKF	Combinatorial Kalman filter, 23, 181
CKM	Cabibbo–Kobayashi–Maskawa, 5
CMB	Cosmic microwave background, 8
CMS	Compact Muon Solenoid, V, 20, 21, 23, 25, 27, 56, 231
CoG	Center of gravity, 46, 118, 145, 232
CR	Color reconnection, 177, 196, 206, 217, 221, 226
CSC	Cathode strip chamber, 26
DAC	Digital-to-analog converter, 58, 76, 87, 94, 109, 113, 119, 235, 241
DAQ	Data acquisition, IX, 27, 58, 75, 76, 80, 86, 88, 92, 98, 103, 121, 231
DCI	Double column interface, 58
DCol	Double column, 55, 59, 60, 61, 117
DESER160	160 MHz deserializer module, 76
DESER400	400 MHz deserializer module, 76, 77
DESY	Deutsches elektronen-synchrotron, 57, 66
DT	Drift tube, 26
DTB	Digital test board, 76, 77, 87, 94, 109, 113, 119, 235
DUT	Device under test, 50, 91, 92, 123, 235
DY	Drell–Yan, 176, 177, 194
EB	Barrel electromagnetic calorimeter, 24

ECAL	Electromagnetic calorimeter, 24, 180
EE	Endcap electromagnetic calorimeter, 22
ES	Preshower electromagnetic calorimeter, 24
EWSB	Electroweak symmetry breaking, 7, 15, 161
FED	Front-end driver, 22, 44, 66, 77
FIFO	First-in first-out, 61
FPGA	Field programmable gate array, 27, 76
FSM	Finite-state machine, 101
GBL	General broken lines, 48, 73, 93, 106, 122
GSW	Glashow–Salam– Weinberg, 4, 7
HAL	Hardware abstraction layer, 79
HB	Barrel hadronic calorimeter, 25
HCAL	Hadron calorimeter, 25, 29, 180
HDI	High-density interconnect, 63
HE	Endcap hadronic calorimeter, 25, 29
HF	Forward hadronic calorimeter, 19, 25
HL-LHC	High-luminosity LHC, 28
HLT	High-level trigger, 27, 31, 32, 179, 259
HO	Outer hadronic calorimeter, 25
HPD	Hybrid photodetector, 25
I^2C	Inter-integrated Circuit, 58, 63, 77
IP	Interaction point, 18, 20, 55, 65, 139, 181
JER	Jet energy resolution, 194
JES	Jet energy scale, 194
L1	Level 1 trigger, 27, 28, 30, 55, 58, 60, 173
LHC	Large Hadron Collider, V, VII, 9, 10, 17, 20, 21, 55, 62, 96, 130, 159, 231, 234
LHCb	Large Hadron Collider beauty, 20
LO	Leading order, 5, 176
LS1	Long shutdown 1, 18, 20, 22, 25, 27, 231
M26	Mimosa26, 94, 95, 96, 97, 98, 235
MAD	Mean absolute difference, 73, 112, 126, 135
MAPS	Monolithic active pixel sensor, 41, 94
MC	Monte Carlo, XII, XVII, 14, 129, 166, 169, 170, 171, 173, 193, 200, 203
MIP	Minimum ionizing particle, 26, 35, 42, 87
MP-II	Millepede-II, 49, 106, 107, 122
MPV	Most probable value, 42, 74, 115, 126, 128, 129, 133, 141, 241
NLO	Next-to-leading order, VII, XII, 5, 161, 163, 166, 167, 171, 174, 175, 176
NNLO	Next-to-next-to-leading order, 174, 176
PCB	Printed circuit board, 93, 96, 235
PDF	Parton distribution function, 9, 10, 163, 170, 171, 173, 175, 195, 196

PF	Particle flow, 23, 25, 180
PLL	Phase-locked loop, 61
PMT	Photomultiplier tube, 29, 92, 95, 98
PS	Proton Synchrotron, 17
PUC	Pixel unit cell, 58, 59, 60, 72, 82, 83, 84, 87, 120, 124, 148
QCD	Quantum chromodynamics, VII, XI, 3, 10, 20, 160, 162, 163, 169
QFT	Quantum field theory, 2
RC	Run control, 99
RCI	ROC controller and interface, 58, 60, 62
REF	Timing reference, 95, 96, 106, 117, 121, 124, 125, 128, 130
RMS	Root mean square, 50, 51, 72, 87, 93, 95
ROC	Readout chip, X, XI, 41, 55, 56, 57, 58, 63, 76, 78, 81, 82, 84, 87, 96, 98, 103, 111, 115
RPC	Remote procedure call, 79, 80
RPC	Resistive plate chamber, 26
SCM	Single chip module, 57, 69, 82, 93, 95, 96, 98, 103, 112, 113
SCR	Space-charge region, 38, 39, 40
SEU	Single event upset, 29, 57, 66
SiPM	Silicon photomultiplier, 25, 29
SM	Standard model, IX, XI, 1, 2, 3, 5, 6, 8, 14, 20
SPS	Super proton synchrotron, 18
SVD	Singular value decomposition, 213
TBM	Token bit manager, 56, 57, 63, 64, 66, 76, 77
TLU	Trigger logic unit, 97
UE	Underlying event, 11, 172, 173, 196, 197, 204, 228, 258