

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 $\sqrt{s} = 13 \text{ TeV}$.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 $\sqrt{s} = 8 \text{ TeV}$.

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 $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ 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.

¹Natural 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 ($t\bar{t}$) is about $\sigma = 245$ pb, and therefore, about five million $t\bar{t}$ events have been produced at the LHC in the 19.7 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 $t\bar{t}$ production cross section. The currently most precise combination of direct measurements performed by the CMS collaboration yields a mass of $m_t = 172.44 \pm 0.13(\text{stat}) \pm 0.41(\text{syst})$ 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 $t\bar{t}$ events, where both W bosons decay into lepton–antineutrino pairs, and which contain additional jet activity ($t\bar{t} + \text{jet}$). The observable ρ_S is proposed in [12] and is defined as the inverse of the invariant mass of the $t\bar{t} + \text{jet}$ 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 $t\bar{t} + \text{jet}$ 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 $t\bar{t} + \text{jet}$ 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.

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CMS Pixel Detector Upgrade and Top Quark Pole Mass
Determination

Spannagel, S.

2017, XXVII, 274 p. 136 illus., 74 illus. in color.,

Hardcover

ISBN: 978-3-319-58879-7