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Evolution Studies of the CMS Electromagnetic Calorimeter

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Supervisor's Foreword

The Standard Model (SM) of Particle Physics describes very successfully the fundamental building blocks of matter and the interactions among them. It has been tested to extremely high precision in many experiments. However, most likely the SM is only a "low-energy" effective theory of a more general theoretical framework, expected to be valid way beyond the energy scales probed so far. Currently, particular interest is devoted to the electroweak energy scale of about a Tera electronVolt (TeV), which is probed by the LHC accelerator and its experiments at CERN. In fact, during the years 2010–2012 the LHC has delivered proton–proton collisions at the center-of-mass energies of 7 and 8 TeV. The main questions addressed at this high-energy collider setup are the origin of electroweak symmetry breaking and the related question of the existence of one or more scalar Higgs bosons, with the spectacular discovery of a new boson, consistent with the hypothesis of an SM Higgs boson, in 2012. Further important efforts are devoted to the searches for physics beyond the SM, such as the appearance of supersymmetric particles. Supersymmetry (SUSY) is a theory, which introduces a new fundamental symmetry between fermions and bosons, and thus ultimately between matter and force particles. This theory has had enormous theoretical and experimental attention for many years, and can be considered as one of the most studied possibilities for an extension of the SM. The reason for the popularity of this model is its potential to solve a number of problems arising in the SM. For example, the various coupling constants appear to unite at a very high energy scale, and probably most importantly, the model offers a candidate for the dark matter particle, namely weakly interacting massive particles such as the neutralino. If SUSY particles exist with masses accessible at the LHC, typically they would be produced in coloured pairs, such as squarks and gluinos, which then undergo characteristic decay chains to further SUSY or SM particles. In most cases, a decay chain ends with a lightest stable SUSY particle, which is very weakly interacting and thus leaves the experiment undetected. The experimental signature is thus a considerable missing transverse energy, accompanied by a certain number of hadronic jets and/or leptons. Many searches at the LHC have been developed for such signatures or topologies, characterized by different sensitivities to SUSY particles and different amounts of backgrounds to be controlled.

The data sample, which the LHC has already delivered, represents only a small fraction of the total expected dataset to be collected by the experiments during the coming decade(s). Because of the foreseen increase in luminosity, the detectors will have to operate in an ever more challenging environment, with particular attention to be given to the radiation hardness of detector components and their related longevity and continued excellent performance. In order to respond to these challenges, the CMS experiment will be upgraded in several steps. A first important upgrade will consist in the replacement of the current three-layer pixel detector with a new, four-layer detector in the year-end technical stop 2016–2017. Other extensive R&D studies are targeted toward the replacement of the forward-calorimeter elements in a long shutdown, foreseen around 2023–2024. In all of these cases extensive simulation studies had and have to be carried out, in order to evaluate the performance and physics potential of the proposed detector upgrades.

The thesis of Hannsjörg Artur Weber represents an exceptionally complete approach to the above-mentioned issues, since it consists of an analysis of the 8 TeV dataset targeted at the search for SUSY particles, which has led to some of the world's best limits, as well as of simulation and R&D studies related to the pixel and calorimeter upgrades.

Regarding the data analysis, already during his master thesis he contributed to the so-called M_{T2} hadronic SUSY analysis (M_{T2} is a kinematic observable well-suited for SUSY searches), carried out by members of the ETH Zurich group in the CMS experiment. The analysis, which was published in JHEP, resulted in the world's best limits on squarks and gluinos in the context of the constrained minimal SUSY extension of the SM. For the 8 TeV M_{T2} hadronic SUSY analysis, Hannsjörg became one of the two leading members of the analysis team, and, notably, the driving force behind most of the data-driven background predictions which constitute one of the core elements of this analysis and which have gained considerable attention and recognition within the CMS collaboration. Again, the analysis resulted in some of the world's best limits on the production of coloured SUSY particles. The corresponding publication has been submitted to JHEP in February 2015.

The second part of his thesis describes the work carried out in the context of the CMS upgrade efforts. In a first study based on simulations, he evaluated the physics potential of the proposed pixel detector upgrade, by taking a special version of the M_{T2} analysis, which also requires hadronic jets tagged as originating from b-quarks. He showed that the new detector would allow for a substantial improvement in terms of b-jet selection efficiency, and thus improves the performance of analyses, which are based on final states including b-jets. Finally, Hannsjörg has performed an in-depth study of the response evolution of the CMS electromagnetic calorimeter endcaps. The scintillating crystals and light detectors in this part of the calorimeter are expected to suffer from the radiation environment at the LHC. Indeed, changes are revealed by a monitoring system using laser light injection to track the overall response evolution. However, it is difficult to disentangle the contributions of the different detector components, and to understand their origin: whether they are dependent on the rate of exposure and possibly recovering spontaneously, or whether they are proportional to the cumulated exposure. In order to gain a better understanding, he performed a study of monitoring data taken in-situ, trying to find a correlation with component quality parameters measured during detector construction. The study performed by Hannsjörg has allowed to observe such correlations, and to disentangle the order of magnitude of the various contributions. As such, it represents an important input to the ongoing discussions within CMS for selecting the best possible upgrade solutions.

With this thesis, Hannsjörg Artur Weber has very clearly shown to have a deep understanding of LHC physics, and to be able to carry out very involved data analyses, in an independent manner and using innovative approaches. Furthermore, he has made important contributions to the upgrade activities of the CMS experiment. The amount, quality and impact of the results obtained during his Ph.D. studies, covering a broad spectrum of experimental issues, are rather exceptional. I am very happy and proud that his work has been selected for publication in the Springer Theses Series.

Zurich, Switzerland
May 2015

Prof. Günther Dissertori

Abstract

Over the past decades, the standard model of particle physics has been proven to accurately describe the vast majority of the experimental observations within particle physics. The discovery of a boson at a mass of about 125 Gev seems to provide the last missing piece of the standard model, the Higgs boson.

Despite this success, there are some phenomena, for which the description of the standard model is insufficient. In order to surmount these shortcomings, new-physics models have been advanced. One popular model is supersymmetry, which solves several of the deficiencies of the standard model. Supersymmetry extends the description of the standard model by adding a symmetry between fermions and bosons: the elementary particle spectrum is at least doubled.

In this dissertation, a search for supersymmetry in fully hadronic final states is presented. The search analyzes proton–proton collision data, collected at $\sqrt{s} = 8$ TeV with the Compact Muon Solenoid experiment at the Large Hadron Collider. The data correspond to an integrated luminosity of 19.5 fb^{-1}.

The search uses the variable M_{T2} to discriminate between events coming from standard model processes and signal events. The variable is a generalization of the transverse mass for events containing two pair-produced particles, where both particles decay at least to one detected and one undetectable particle. Selecting events with high values of M_{T2} reduces the contribution from standard model processes, in particular multijet events, and enhances the sensitivity for signal events for a large variety of supersymmetric models.

The signal regions of this search are defined by the jet and b-tagged jet multiplicities, the hadronic energy in the event, and the value of M_{T2}. The combined information of multiple signal regions yields a high sensitivity for the production of the partner particles of both gluons and quarks, regardless of the quark flavor, for a wide range of particle masses.

The event yields in the signal regions stemming from standard model processes are estimated by prediction methods that use data from control regions orthogonal to the signal regions definition. No significant excess over the expected numbers of background events is observed. The comparison of data yields and predictions is used to set exclusion limits on various models of supersymmetry.

Beyond this search in hadronic final states, the potential of a search for the pair production of supersymmetric partners of the top quark is assessed using events containing two charged leptons. Several signal discriminating variables have been tested, such as variants of the M_{T2} variable or a discriminant based on the examination of the event kinematics.

The second part of this dissertation contains two studies related to the upgrade program of the Compact Muon Solenoid detector.

The physics performance of the pixel detector upgrade, which is foreseen to happen in 2017, is evaluated in the first study. Based on the event selection of the so-called $M_{T2}b$ search for supersymmetry, performed in 2011, the focus of the study is the improvement of identifying jets, which originate from bottom quark hadronization. For the tested model, an increase of 20 % in the signal selection efficiency is observed for a fixed rate of misidentifying light-quark or gluon jets as bottom-quark jets.

In the final study presented in this dissertation, the long-term evolution of signals produced in the forward part of the electromagnetic calorimeter of the Compact Muon Solenoid experiment is analyzed. The lead–tungstate crystals, which act both as absorber and scintillator, are the heart of the calorimeter. The scintillation light is read out by vacuum phototriodes in the forward part of the detector.

The transparency of the crystals decreases under radiation. In order to measure and correct for these transparency changes, a light monitoring system has been installed within the calorimeter.

Several sources are known to contribute to the transparency decrease. The goal of this study is to disentangle various contributions to the signal change. In order to achieve this, measurements, performed during quality assurance tests prior to the construction of the detector, are correlated with signal changes observed in monitoring data during proton–proton collision data taking. Pseudorapidity-dependent contributions are singled out: ionizing damages to crystals, damages to the vacuum phototriodes, and possible cumulative damages to crystals. The results of this study are compared with predictions, which are based on laboratory and testbeam results and are used in studies for possible detector upgrades. The comparison indicates that the modeling of the predictions is satisfactory.

Preface

Concepts of fundamental states or elements have been developed independently by several ancient civilizations several centuries before the Common Era, such as the concept of indestructible particles, which was devised in Greece and India, for example. However, the scientific discipline of particle physics is rather young. The first elementary particle to our current knowledge, the electron, was only discovered at the end of the nineteenth century. The discovery of quantum mechanics and special relativity, around the same time, allowed for the development of theories of the fundamental interactions. The first successful description of interactions between fundamental particles, quantum electrodynamics, was developed only in the 1940s.

During the past century, huge efforts on both theoretical and experimental sides have led to the current description in particle physics, the standard model (SM) of particle physics. It describes, within the common framework of relativistic quantum field theory, the interactions between elementary particles for three out of the four known fundamental forces: the strong force described by quantum chromodynamics, and the weak and electromagnetic forces, described by the electroweak theory. For gravitation, the "oldest" known fundamental force, no successful description at short distances exists. Up to the time of this writing, 17 elementary particles (not counting the antiparticles) have been observed: six quarks, six leptons, four gauge bosons, and a boson, which is likely the Higgs boson.

The observations of a huge amount of experiments have proven the validity of the SM to an extremely high precision for all accessible energy scales. Despite this unprecedented success of the SM, several theoretical indications and experimental measurements clearly point to physics beyond the SM. The observation of neutrino oscillations or the evidence of dark matter find no explanation within the SM. The missing description of quantum gravity, which is important for energies around the Planck scale, $M_{\text{Planck}} \sim 10^{18}$ GeV, requires a new theoretical framework. These and other arguments place the SM as an effective low-energy theory, valid for energies up to the electroweak scale, $v \sim 246$ GeV.

In order to overcome some of the shortcomings of the SM, multiple theories have been developed. One very popular theory is supersymmetry (SUSY). The SM is extended by an additional symmetry between bosons and fermions: for each elementary particle in the SM, there exists a partner particle, which differs in spin by one half. Because of the breaking of the symmetry, these particles are much heavier than their SM counterparts and have not yet been observed. The model of SUSY provides elegant solutions to multiple problems, for example, the problem of dark matter mentioned above: the lightest new particle within the SUSY framework could be a candidate for the dark matter particle.

Yet, no observation of supersymmetric particles or other evidence for SUSY have been found so far.

With the construction of the Large Hadron Collider (LHC), a new energy regime has been made accessible: the energy frontier has been pushed up to the TeV scale. If supersymmetric particles exist, they will likely have masses around this scale. Therefore, the general purpose detectors at the LHC should be able to discover them.

In this dissertation, a search for supersymmetric particles produced in proton–proton (*pp*) collisions is presented. The search is performed using data collected by the Compact Muon Solenoid (CMS) experiment at a center of mass energy of $\sqrt{s} =$ 8 TeV. The data sample corresponds to an integrated luminosity of 19.5 fb^{-1}. This search uses primarily the kinematic variable M_{T2} for discriminating between new physics candidate events and events from SM processes. This variable is a generalization of the transverse mass to the case of the pair production of two particles, which both decay semi-invisibly.

The variable M_{T2} is also used in a study for evaluating the feasibility of a search for the production of supersymmetric partner particles of the top quark in events containing two charged leptons. In many SUSY scenarios, the supersymmetric top quark partner is the lightest strongly produced supersymmetric particle. Therefore, several dedicated searches for this particle are designed. The study presented here shows the possibility of using various variables to discriminate between the SUSY signal events and events from the main SM background process, $t\bar{t}+$ jets.

It has been decided that the full potential of the LHC will be exploited by an upgrade of the LHC machine around 2022. The upgrade will increase the instantaneous luminosity of the LHC by approximately a factor ten, thus allowing for the collection of *pp* collision data corresponding to about 3000 fb^{-1}.The upgrade will require also the experiments to be upgraded.

Already before the year 2022, the innermost detector of the CMS experiment, the pixel detector, will have to be replaced because of radiation damages. The replacement will be used to change the pixel detector design. In this dissertation, a study of the physics performance of this upgrade is shown with focus on the capability of tagging jets, which come from b-quark hadronization. The study is performed in the context of SUSY using the event selection of the $M_{\text{T2}}b$ search, which was performed during 2011 for the analysis of 7 TeV *pp* collision data.

It is expected that by 2022, the forward part of the electromagnetic calorimeter of the CMS experiment will also need to be replaced due to high radiation damages. A study of the long-term evolution of the signals produced in this forward part is presented using in-situ data of the light monitoring system of the calorimeter. Comparisons with laboratory measurements preceding the construction of the CMS experiment are discussed. The correlations between these laboratory measurements and the in-situ data are used to disentangle various components that contribute to the change in signal measurements of the calorimeter.

The thesis is organized as follows: in Chap. 1, the theoretical aspects of the SM relevant for high energy physics are reviewed. Then, in Chaps. 2 and 3, SUSY and consequent signatures at the LHC are introduced. In Chap. 4, the LHC accelerator and CMS detector are described, followed by a description of the reconstruction of basic physics objects in Chap. 5. In Part II of the thesis, the search for SUSY is covered: in Chap. 6, the main search variable, M_{T2} , and its kinematical properties are introduced. This chapter contains also a summary of the SUSY search performed at $\sqrt{s} = 7$ TeV. Chapter 7 is dedicated to the search for SUSY in hadronic final states using the M_{T2} variable with pp collision data collected at $\sqrt{s} = 8$ TeV. In Chap. 8, the feasibility study of a search for the pair production of scalar top quark partners is summarized. In Part III, studies related to the upgrade program of the CMS experiment are presented. After a short review of the upgrade program in Chap. 9, the physics performance study for the pixel detector upgrade is discussed in Chap. 10. Finally, Chap. 11 contains the evolution study of the electromagnetic calorimeter endcap signals. In Chap. 12, a summary is given.

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