Abstract

At the CMS experiment at the Large Hadron Collider (LHC) at the CERN, the main focus is to search for physics beyond the Standard Model as well as the measurement of Standard Model parameters. For these two purposes, it is necessary to determine important performance parameters at the CMS experiment. The here presented thesis contributes in a twofold way to the physics program of CMS.

In the first part of this thesis, a search for physics beyond the Standard Model is presented. It is motivated by supersymmetric models with nearly mass-degenerate lightest neutralinos and next-to lightest charginos. The small mass gap between chargino and neutralino can lead to long lifetimes of the chargino due to phase space suppression. Thus, the chargino can reach the detector before its decay. The here presented search targets chargino lifetimes of $c\tau \approx 1 - 30\,\text{cm}$ where most of the charginos even decay in the first layers of the tracker. This search aims in increasing the search sensitivity of existing searches with respect to these models in a twofold way: First, the inclusion of tracks down to three measurements in the tracking system, and second, the discrimination against Standard Model background by the variable dE/dx, the energy loss per path length. The search is performed on $19.7\,\text{fb}^{-1}$ of data recorded at the CMS experiment at a centre-of-mass energy of 8 TeV. The background is mainly estimated using data-based techniques and consists mostly of fake tracks, i. e. tracks no associated to one single particle. The search is performed in four exclusive signal regions in order to enhance the search sensitivity with respect to different chargino masses and lifetimes. No excess above the Standard Model expectation is found and the supersymmetric parameter space is constrained. The search can exclude supersymmetric models with chargino masses of 100 GeV down to lifetimes of $c\tau = 2\,\text{cm}$ and for masses of 500 GeV down to lifetimes of $c\tau = 70\,\text{cm}$. Current limits could be confirmed and improvements of the order of 10-40 GeV were achieved.

In the second part of the thesis, a measurement of the jet transverse-momentum resolution at 8 TeV at the CMS experiment is presented. In order to exploit the good calorimeter energy resolution of the CMS experiment, the measurement is performed using γ + jet events, where the photon energy can be used as a measure for the true jet transverse momentum. The applied method is based on earlier measurements but is further developed within this thesis in order to consistently account for the influence of additional jet activity on the jet transverse-momentum response. By this development a well behaved method could be ensured.

Zusammenfassung

Am CMS-Experiment am Large Hadron Collider (LHC) am CERN liegt der Hauptfokus auf der Suche nach Physik jenseits des Standardmodells und der Messung der Parameter des Standardmodells. Dafür ist es notwendig, wichtige Leistungsparameter bzw. Kenngrößen des CMS-Detektors zu messen. Die hier präsentierte Arbeit trägt in zweifacher Weise zu dem Physikprogramm des CMS-Experiments bei.

Im ersten Teil wird eine Suche nach neuer Physik, motiviert durch supersymmetrische Modelle mit fast masseentarteten Neutralinos und Charginos, vorgestellt. Falls das leichteste Chargino nur wenig schwerer ist als das leichteste Neutralino, kann dies, wegen des verkleinerten Phasenraums, zu einer langen Lebenszeit des Charginos führen. Die hier präsentierte Suche ist konzipiert für Modelle mit Charginolebensdauern von ungefähr $c\tau \approx 1 - 30\,\text{cm}$. Bei diesen Lebensdauern können die Charginos schon sehr früh im Detektor zerfallen, sogar in den ersten Lagen des Spurdetektors. Daher wird eine Erhöhung der Suchsensitivität im Vergleich zu früheren Suchen in zweifacher Weise versucht zu erreichen. Zum einen durch die Einbindung von sehr kurzen rekonstruierten Spuren, zum anderen durch eine verbesserte Diskriminierung des Standardmodelluntergrunds durch die Variable dE/dx, der Energieverlust pro Weglänge. Die Suche nach hoch ionisierende, kurzen Spuren wird mit 8 TeV Daten, die im Jahr 2012 am CMS-Experiment aufgenommen wurden, durchgeführt. Der Untergrund wird hautsächlich mit datengetriebener Methoden bestimmt und besteht zumeist aus falsch rekonstruierter Spuren, d.h. Spuren, die nicht durch ein einziges Teilchen verursacht wurden. Es konnte kein Überschuss beobachtet werden. Die Suche schließt mit diesem Ergebnis Modelle mit Charginomassen von 100 GeV bis runter zu einer Lebensdauer von $c\tau = 2\,\text{cm}$ und Massen von 500 GeV bis runter zu $c\tau = 70\,\text{cm}$ aus. Damit konnten bestehende Ausschlussgrenzen bestätigt und stärkere Ausschlussgrenzen zwischen 10-40 GeV erzielt werden.

Im zweiten Teil dieser Arbeit wird die Messung der Jetimpulsaufloesung bei einer Schwerpunktsenergie von 8 TeV vorgestellt. Um die sehr gute Energieauflösung des elektromagnetischen Kalorimeter am CMS-Experiment auszunutzen, wird die Messung mithilfe von $\gamma + \text{jet}$ Ereignissen durchgeführt. Dabei wird die Transversalimpulsbalance zwischen Jet und Photon, unter Vernachlässigung von weiterer Abstrahlung, ausgenutzt. Durch die Weiterentwicklung der Methode, die den Einfluss der Richtung weiterer Jets in einem Ereignis auf die Jet-p_{T}-Response berücksichtigt, konnte eine gut funktionierde Methode sichergestellt werden. Relative Auflösungsunterschiede zwischen gemessener und simulierter Daten liegen zwischen 7 und 20%.

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Part 1

Introduction

With the discovery of the Higgs boson at the LHC in the year 2012, the last missing piece of the Standard Model of particle physics was found [1, 2]. Thus, all particles contained in the Standard Model are discovered and all of its parameters are measured, many of them with accuracies at the per-mille level. Up to now, the Standard model has been tested at many particle physics experiments and has proven its ability to explain - and even predict - experimental results in a remarkable way.

Nonetheless, there are strong reasons to believe that the Standard Model is not the ultimate theory of particle physics. Experimental observations as well as theoretical considerations have led to the belief that there exists physics beyond the Standard Model. For instance, the observation of Dark Matter cannot be explained from a particle perspective within the Standard Model since no suitable Dark Matter candidate is contained. From a theoretical point of view, a major concern is related to the occurrence of quadratic divergencies in the calculation of the Higgs boson mass at higher radiative orders. The Higgs boson mass is measured at a value of around 125 GeV, which is considered very low regarding the huge radiative corrections at the Planck scale ($\sim 10^{19}$ GeV). This raises the question of what kind of mechanism is responsible for the stabilisation of the Higgs boson mass at the electroweak scale. Among others, these shortcomings of the Standard Model have led to strong efforts to develop theories that go beyond the Standard Model of particle physics.

One of these theories is able to solve the above mentioned problems by imposing a fully new symmetry into the Lagrangian formulation of particle physics, a so-called supersymmetry (SUSY). This symmetry relates bosons and fermions by new fermionic generators and leads to the prediction of a supersymmetric partner particle for each of the particles contained in the Standard Model. This could have drastic implications for the phenomenology of particle physics, since a doubling of the particle content is predicted. Therefore, a variety of searches for supersymmetric particles has been performed at many particle physics experiments.

This PhD thesis presents a search for supersymmetric particles in 19.7 fb^{-1} of data, taken in the year 2012 at a centre-of-mass energy of 8 TeV at the CMS detector. The search is motivated by supersymmetric models with nearly mass-degenerate lightest ($\tilde{\chi}_1^0$) and next-to lightest ($\tilde{\chi}_1^\pm$) supersymmetric particles that have not yet been investigated by existing SUSY searches. A small mass splitting between the two particles can lead to a long-lifetime of the next-to lightest supersymmetric particle $\tilde{\chi}_1^\pm$ because of phase space suppression. The charged $\tilde{\chi}_1^\pm$ can therefore appear as a reconstructed track in the inner tracking system of the CMS detector. At rather low $\tilde{\chi}_1^\pm$ lifetimes, the $\tilde{\chi}_1^\pm$ decays inside the tracker and the reconstructed track can be very short. Furthermore, since the masses of the supersymmetric particles are in general higher than their Standard Model partners, $\tilde{\chi}_1^\pm$

can be heavy and can therefore deposit much higher energies in the tracker compared to minimally ionising Standard Model particles. Therefore, the analysis strategy of the here presented analysis is to search for highly ionising, short tracks. It is the first analysis that incorporates tracks with down to three measurement and that makes use of the energy information of the silicon pixel tracker, which has been subject to an energy calibration within this thesis.

The second research objective of this thesis is a measurement of the jet transverse-momentum resolution at a centre-of-mass energy of 8 TeV at CMS. The knowledge of the jet p_{T} resolution is a crucial ingredient for many analyses at CMS, e. g. the measurement of the dijet cross section [3] and searches for physics beyond the Standard Model that rely on a good understanding of missing energy originating from wrongly measured jets [4].

In order to exploit the good calorimeter energy resolution of the CMS experiment, the measurement is performed using $\gamma + \text{jet}$ events, where the photon energy can be used as a measure for the true jet transverse momentum. The applied method is based on earlier measurements [5, 6] but is further developed within this thesis in order to consistently account for the influence of additional jet activity on the jet transverse-momentum response.

The thesis is structured into six main parts.

Part 2: This part summarises the theoretical foundations, comprising an introduction to the Standard Model of particle physics as well as to its supersymmetric extensions. A special focus is on the theoretical description and phenomenology of long-lived particles in supersymmetric models.

Part 3: Within this part, the experimental setup is presented, including an introduction to the Large Hadron Collider and the CMS experiment as well as a description of the algorithms used for event reconstruction and particle identification at CMS. Finally, a short introduction into the techniques of event simulation is given.

Part 4: In this part, the search for highly ionising, short tracks is presented. It starts with a motivation and an outline of the general search strategy. Afterwards, the calibration of the silicon pixel tracker is described and its impact on the search is discussed. Subsequently, the event selection is described and the background estimation methods are introduced. Finally, the results are presented and interpreted in the context of supersymmetric models with long-lived $\tilde{\chi}_1^{\pm}$. The last chapter of this part is devoted to a conclusion and discussion of the most important findings.

Part 5: This part presents the measurement of the jet transverse-momentum resolution in $\gamma + \text{jet}$ events recorded at CMS at $\sqrt{s} = 8\,\text{TeV}$. It starts with a motivation and a presentation of the general approach of the measurement. The introduction of the

event selection is followed by a thorough description of the methodology. Afterwards, the systematic uncertainties are discussed. Finally, the results are presented, followed by a conclusion and discussion.

Part 6: This part concludes and summarises the most important results of this thesis.

Part 2

Summary

In the year 2012, a variety of different searches and measurements were performed at the CMS experiment. The main focus was to search for physics beyond the Standard Model as well as to measure Standard Model parameters and important performance parameters of the CMS detector. This thesis contributed in a twofold way to the physics program of CMS. First, a search for supersymmetric particles by the selection of highly ionising, short tracks was performed and second the jet transverse-momentum resolution was measured in $\gamma +$ jet events at 8 TeV. The following paragrafs summarise the two presented analyses. A more detailed discussion about the most important findings and possible improvements can be found in the last chapters of the corresponding parts, Chapter **??** and Chapter **??**, respectively.

The search for physics beyond the Standard Model by the selection of highly ionising, short tracks was strongly motivated by supersymmetric extensions of the Standard Model that include long-lived charginos decaying inside the tracker into the lightest supersymmetric particle, the neutralino. Because of the higher masses of supersymmetric particles, the chargino is expected to deposit much higher amounts of energies in the tracking system compared to the Standard Model background. Thus, the inclusion of the variable dE/dx can be highly discriminating. Furthermore, the search was designed to target supersymmetric models not yet excluded, i. e. models with chargino lifetimes of the order of $c\tau \approx 1 - 30\,\text{cm}$ where most of the charginos even decay in the first layers of the tracker. Therefore, for the first time, reconstructed tracks down to three tracker hits were incorporated and an energy measurement was performed. For this purpose, energy information from the silicon pixel detector was exploited for the first time at CMS. The energy information provided by the pixel tracker could only be used because a well calibrated tracking system was ensured. This was achieved by the calibration of the pixel tracker energy information which was performed within this thesis. The inclusion of pixel energy information could increase the background suppression for a given signal efficiency significantly (cf. Fig **??**).

The background expectation was estimated mainly with data-based techniques and consisted mostly in fake tracks, i. e. tracks that are not associated to one single particle. Fake tracks can easily mimic the signal sinature because of their typically large dE/dx values. A selection was performed in four different signal regions in order to increase the search sensitivity to different chargino lifetimes and masses. The major challenges of this search consisted in the estimation of the Standard Model background because of the low event yield in most of the control regions. Therefore, the search sensitivity is mainly limited by systematic uncertainties arising from limited size of simulated samples as well as control regions in data.

The search for highly, ionising short tracks was performed with $19.7\,\text{fb}^{-1}$ of 8 TeV data

recorded at the CMS experiment in the year 2012. The results were compatible with Standard Model expectations. Thus, this result was used to constrain the supersymmetric parameter space with wino-like charginos. With this search supersymmetric models with long-lived charginos down to lifetimes of 2 cm for chargino masses of 100 GeV and down to 70 cm for masses of 500 GeV could be excluded. Current limits could be confirmed and improvements of the order of 10-40 GeV were achieved.

The second contribution of this thesis consists in the measurement of the jet transverse-momentum resolution at 8 TeV at the CMS detector. It exploits the high calorimeter energy resolution and use γ + jet events in order to use the photon as a measure of the true jet transverse momentum. The jet p_{T} resolution is a crucial ingredient for analyses at CMS relying on a good understanding of the quality of the jet p_{T} measurement, e. g. physics beyond the Standard Model where QCD-multijet background plays a major role [4, 7, 8] or Standard Model measurements of the QCD cross section [3] or top quark differential measurements [9]. The method of the resolution measurement is based on earlier methods but is the first measurement that accounted for the fundamental non-Gaussian behaviour of the measured resolution in exclusive bins of further jet activity. The Gaussian behaviour can be recovered when separating events by the direction of further jets in the event. By this separation the validity of the method could be retained and a well performing method was achieved.

Since the main application of the resolution measurement is the adjustment of the simulated resolution to the resolution measured in data, the results are presented as data-to-simulation scale factors. In various pseudorapidity regions up to $|\eta| = 2.3$, the scale factors vary between 7% and 20% with uncertainties between 3% to 8%. They are in agreement with the jet p_{T} resolution measurement performed on dijet events [10].

To conclude, this thesis provides a variety of different methods that are useful for the analysis of collision data at high energies.

It provides insights in physics objects - very short reconstructed tracks - that were not used at CMS so far. Furthermore, for the first time, ionisation losses are measured taking energy information from the pixel silicon tracker into account. Since the use of dE/dx will gain more and more importance in the search for long-lived particles due to the exploration of much higher energies, this thesis can contribute to an sensitivty increase by exploiting pixel information, too.

Furthermore, the use of dE/dx as disciminating variable will gain more and more importance in the search for long-lived particles because of the exploration of much higher energies. Furthermore, a energy calibration of the pixel tracker was performed which could especialy be interesting beacuse of dE/dx.

In the second part of the thesis, the further development of the methodology of an important measurement, namely the jet p_{T} resolution measurement, ensured that the method can still be used. It discussed a precise measurement of an important variable of detector preformance.

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