Final Report

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1) Summary (max. 1 DIN A4 page)

The main topic of this project is the search for Supersymmetry (SUSY) at the LHC experiment. The group started before the first run of the LHC and was therefore able to analyze the full data taken at center-of-mass energies of 7 and 8 TeV.
Before the start of the LHC, it was expected that supersymmetric particles would best be seen in analyses containing high-energetic jets due to the high mass of the supersymmetric particles, and large missing transverse energy due to the weakly-interacting lightest SUSY particles which would leave the detector without any trace. In the proposal of this project, I had put the focus on final states containing in addition one or two leptons of the first and second generation, which on the one hand would allow to further identify possible superpartners in the decay chain and on the other hand efficiently reduces the background from QCD multijet events, one of the most critical backgrounds that are difficult to describe especially at the startup of the new machine.
After the analysis of the first data it became clear that the superpartners of the first and second generation are probably heavier than expected, while for naturalness considerations especially the superpartners of the third generation and the gluino, the superpartner of the gluon are expected to be light. In addition, the gluino would decay preferentially via (virtual) sparticles to third-generation squarks. Therefore, I focused the research in my group on searches including b-tagged jets and published one of the first papers on the search for gluinos decaying to third-generation squarks on the data taken in 2011 with a center-of-mass energy of 7 TeV. We also investigated the direct production of the top squark, which has a very low production cross section and was first possible with the data taken in 2012 at 8 TeV. Again, the first paper published on top squark production within CMS is the paper with contribution of my group.
In addition, we also contributed to studies of future detector upgrades, such as the Phase-1 Upgrade, which will take place in 2018/19, where we studied SUSY processes for the Technical Design Reports for the Level-1 Trigger and the Hadron Calorimeter.
Due to this work I was selected to become the leader of the SUSY Future Analyses Subgroup in 2013/14 and coordinated the contributions of the SUSY group to the Snowmass 2013 effort in the U.S. and the ECFA Workshop on the High-Luminosity LHC (HL-LHC) in 2013. Currently I am coordinating the studies for the Technical Proposal for the HL-LHC and the next ECFA Workshop on the HL-LHC in autumn 2014.
The group is also active in detector and hardware development, with focus on the CMS Hadronic Calorimeter. At the beginning of the project we were focusing on energy weighting to improve the resolution of the Hadronic Calorimeter, my group is now involved in the upgrade of the Hadron Calorimeter from an old readout technology (based on VME) to μTCA, including the successful development of FPGA firmware.

2) Work and Results Report

a) Starting point (max. 1 DIN A4 page)

At the beginning of the project, the LHC did not take any data yet, but up to then the Standard Model of particle physics had proven to be a very successful model, describing three of the four known fundamental forces: the weak, the electromagnetic and the strong force. The fundamental particles in the Standard Model are the quarks and leptons (and their antiparticles), the gauge bosons (mediators of the forces), and the Higgs boson, which was discovered at the first LHC run with the data taken in 2011/2012. However, the Standard Model does not include the fourth force, the gravity, and cannot answer a number of open-ended questions, among them:

- Grand unification: Do the electroweak and the strong force unify at large energies?
- Dark Matter: Can particle physics help to explain cosmological observations?
- Hierarchy problem: Are the corrections to the mass of the Higgs particle over 30 orders of magnitude larger than the mass itself or do new unknown particles cancel these corrections?
- Vacuum stability: Is our universe in a metastable state?

These open questions suggest that the Standard Model cannot be a complete theory and there must be new physics beyond the Standard Model. With the startup of the LHC, a new energy range has been opened, allowing me to search for new particles beyond the Standard Model with the highest ever reached energy.

A possible extension of the Standard Model is the theory of Supersymmetry (SUSY), which predicts several new particles that are directly observable if their masses are in the energy range of the LHC. In SUSY, to each Standard Model particle at least one supersymmetric partner particle is assigned, which has the same quantum numbers except for the spin, which differs by ½. If the symmetry would be perfect, the partner particles would also have the same masses as the Standard Model particles and would, therefore, have already been found. As this is not the case, we assume that the symmetry is broken, leading to higher masses of the supersymmetric partner particles, which have still to be discovered. In order to solve naturally the hierarchy problem, the masses of the supersymmetric particles, especially of the partner particle of the top quark which is responsible for one-loop corrections of the Higgs mass, should be (at least partly) at the TeV scale and hence in the reach of the LHC.

The goal of the project was the discovery of the SUSY, with special emphasis on the search for directly produced top-squark pairs, and for top squarks in the decays of the gluino (the partner particle of the gluon), which is also expected to not be too heavy as it is correcting the Higgs mass on the two-loop level.

The cancelling of the radiative corrections to the Higgs mass is not the only advantage of Supersymmetry, it also answers a large number of other open questions. For example, it yields a viable Dark-Matter candidate, can lead to the unification of the electromagnetic, weak and strong force, incorporates CP-violation and even offers a possibility to include gravity, which is not possible in the Standard Model.

b) Description of the results (max. 4 DIN A4 pages)

Search for gluino production and decay to third-generation quarks in the single-lepton channel

This search is the first CMS analysis explicitly looking for third-generation particles. It is based on the full dataset obtained in 2011, corresponding to 5 fb^{-1} in final states with a single electron or muon, multiple jets, including some identified as originating from b-quarks and missing transverse energy. Gluino pair production can lead to events containing four third-generation quarks, resulting in an excess of events with large b-jet multiplicities, which is exploited by this dedicated analysis.

The search is performed in signal regions defined using the scalar sum of the jet transverse momenta, the missing transverse energy, and the b-jet multiplicity.
The dominant SM background processes contributing to the search topology are top-quark pair production and inclusive W-boson production in association with energetic jets. Smaller contributions are due to single-top production, QCD multijet events, and Drell-Yan production and decay to lepton pairs in which one lepton remains undetected. While simulation provides a good description of these contributions, more reliable estimates of the backgrounds with smaller uncertainty can be obtained from data, here with a factorization method.
The results are compatible with the Standard Model prediction and interpreted in a constrained minimal supersymmetric model as well as in a simplified model. In the context of the constrained minimal supersymmetric extension of the standard model with parameters tan β = 10, A_0=0 GeV, and μ >0, values of $m_{1/2}$ below about 450 GeV are excluded for m_0 in the range of about 200 GeV to about 800 GeV. In the parameter plane of the gluino and LSP masses of a simplified model that features four top quarks in the final state, exclusion reaches to gluino masses of about 870 GeV. At a gluino mass of 750 GeV, LSP masses below 240 GeV are excluded.

Search for direct top squark production in the single-lepton channel

This analysis led to the first publication of CMS on direct top-squark production, based on an integrated luminosity of 19.5 fb^{-1} of pp collisions collected in 2012 by the CMS experiment at the LHC at a center-of-mass energy of 8 TeV.
This search is motivated by the consideration that relatively light top squarks, with masses below ~1 TeV, are necessary if SUSY is to be the natural solution to the hierarchy problem. The search presented here focuses on two decay modes of the top squark, either to a top quark and the lightest neutralino, or a bottom quark and the lightest chargino, which is unstable and will decay to a W boson and the lightest neutralino as well. The analysis is based on events where one of the W bosons decays leptonically and the other hadronically. This results in one isolated lepton and four jets, two of which originate from b quarks. The two neutralinos and the neutrino from the W decay can result in large missing transverse momentum.
The largest backgrounds in this search arise from events with a top-antitop quark pair where one top quark decays hadronically and the other leptonically, and from events with a W boson produced in association with jets. These backgrounds, like the signal, contain a single leptonically decaying W boson. The transverse mass M_T, calculated from the transverse missing energy and the lepton transverse momentum, has a kinematic endpoint at the W mass for these backgrounds, while for signal events, the presence of LSPs in the final state allows M_T to exceed the W-boson mass.
Hence we search for an excess of events with large M_T.The dominant background with large M_T arises from the top-antitop events where both W bosons decay leptonically but with one of the leptons not identified. In these events the presence of two neutrinos can lead to large values of missing transverse energy and M_T. To reject this background, a special kinematic variable is exploited, which is defined as the minimum “mother” particle mass compatible with all the transverse momenta and mass-shell constraints.
No significant excess in data is observed above the expectation from standard model processes. The results are interpreted in the context of supersymmetric models with pair production of top squarks that decay either to a top quark and a neutralino or to a bottom quark and a chargino. For small mass values of the lightest supersymmetric particle, top-squark mass values up to around 650 GeV are excluded.

Search for Supersymmetry in di-lepton channels

Searches for Supersymmetry in di-lepton channels can be divided into same-sign and opposite-sign di-lepton searches. The advantage of same-sign searches lies in the strong background reduction by the same-sign requirement, while the opposite-sign search offers the opportunity to measure mass edges in case of the production of the leptons in one decay chain of supersymmetric particles, e.g. the decay of the second lightest neutralino to a slepton and a lepton, with the slepton again decaying to a lepton and the lightest neutralino. One PhD thesis has been written on the same-sign di-lepton analysis based on the 7 TeV dataset, and one PhD thesis based on 8 TeV data has been performed on the opposite-sign di-lepton search.

The main background in the same-sign search, where at leading order no Standard Model processes with reasonably large cross section is expected, comes from ‘fake’ leptons, e.g. jets misidentified as electrons, and is determined from data with a tight-to-loose method. Also charge mismeasurement can lead to a signal-like topology, especially in Drell-Yan events. The mismeasurement rate is also determined from data, by determination of the ratio of same-sign and opposite-sign events with the invariant di-lepton mass within a window around the Z-boson mass.

Investigation of a SUSY model discoverable at the LHC and the ILC

Simplified models have become a widely used and important tool to cover the more diverse phenomenology beyond constrained SUSY models. However, they come with a substantial number of caveats themselves, and great care needs to be taken when drawing conclusions from limits based on the simplified approach. To illustrate this issue with a concrete example, we examine the applicability of simplified model results to a series of full SUSY model points which all feature a small stau-LSP mass difference, and are compatible with electroweak and flavor precision observables as well as current LHC results. Various channels have been studied using the Snowmass Combined LHC detector implementation in the Delphes simulation package, as well as the Letter of Intent or Technical Design Report simulations of the ILD detector concept at the ILC. We investigated both the LHC and ILC capabilities for discovery, separation and identification of all parts of the spectrum. While parts of the spectrum would be discovered at the LHC, there is substantial room for further discoveries and property determination at the ILC.

This work has been presented as a Snowmass White Paper, and it is planned to further study these models and publish the refined results in a journal.

Energy weighting for the upgrade of the CMS HCAL

The hadronic calorimeter (HCAL) of CMS is a non-compensating sampling calorimeter with an e/π−ratio of about 1. Consequently, the response for electromagnetic energy depositions is larger than for hadronic ones, which affects the energy measurement. An energy weighting method to compensate for the e/π −ratio is possible if one can identify the electromagnetic- or hadronic-like origin of the energy deposition within a hadronic shower. For the CMS detector upgrade Phase 1 a longitudinal segmentation of the HCAL towers is discussed, improving its longitudinal granularity by a factor of four. This offers the possibility to resolve single parts of particle showers. A possible readout scheme has been investigated. Tabulated weighting factors are used to compensate for the different response of hadronic and electromagnetic energy depositions of simulated pion showers in the hadronic calorimeter.

The weighting improves the relative energy resolution from
$(\sigma_E/E)^2 = [((92.5\pm0.6)\% / E)^2 + ((6.5\pm0.1)\%)^2]\ \mathrm{GeV}^2$ to
$(\sigma_{E,weight}/E)^2 = [((85.5\pm0.5)\% / E)^2 + ((4.4\pm0.1)\%)^2]\ \mathrm{GeV}^2$.
In parallel to our work, the Particle Flow method was established in CMS, which yielded an even larger gain in the energy resolution, so that we decided to not further pursue our efforts.

Development of new backend readout based on the novel Micro-TCA Technology

Due to the larger number of HCAL readout channels, an upgrade of the readout electronics is inevitable. The current system is not able to cope with the increased data volume provided by a calorimeter with higher granularity. In addition, the rate of collisions (luminosity) will increase to a level where zero suppression is no longer as effective as it has been at lower luminosity. Moreover, the demands on efficient event filtering will be much harder to meet with increasing luminosity, and a more flexible and a powerful data path to the calorimeter trigger is needed.
All these requirements cannot be fulfilled with the current backend setup based on the traditional VME technology, and it was decided to take up the challenge of a complete technology swap: an upgrade of the back-end electronics with Micro-TCA technology. The Helmholtz additional funding allowed us to set up a test stand fully reproducing the HCAL backend. With this setup, we developed the communication via the next generation “Clock, Control and Monitoring” (ngCCM) module between the Micro-TCA crate (with a Gigabyte Link Interface Board (GLIB) and the Readout Box (with a “next generation Front End Card” (ngFEC)). Furthermore, the connection between the Data Acquisition (DAQ) PC, the Micro-TCA crate (via the new AMC13 card and a corresponding PC interface) and the Readout Box needs has been established. In addition, the Slow Control (SC) of the Micro-TCA crates has been developed. In this project, one of my PhD students as well as two DESY staff members and two collaborators of the Moscow State University are involved. DESY has established its leading role in this project, which will be applied to other CMS detectors as well.

c) Outlook on future work, sustainability (max. 2 DIN A4 pages)

With the startup of the LHC in 2015, a new energy regime will be opened, allowing for the testing of the most interesting phase space from the naturalness point of view. My group will continue to exist, currently consisting of three DESY fellows who joined my group and 5 PhD students, of which two will work with the new data to arrive in 2015. I intend to perform similar analyses as on the data taken in 2011/2012, and applied in addition for an ERC Consolidator Grant to get more manpower and perform – in addition to the SUSY search – precision measurements of Vector Boson Scattering, which offer the possibility to measure traces of new particles due to their small deviations between measurements by comparing them to equally precise predictions of properties of SM particles. These deviations, arising due to the virtual presence of new particles in quantum loops and in new amplitudes generated by their exchange at tree-level, can be parameterized in Effective Field Theories. Vector boson scattering is especially well suited for such a precision measurement.
The Micro-TCA technology will be used in the future upgrades of the CMS detector, especially in the tracker upgrade, where DESY is heavily involved. The knowledge gained within this project will be of great advantage in the future developments, keeping DESY scientists in the leading position.

d) Potential for application/exploitation (max. 2 DIN A4 pages)

The results achieved by the group in the course of the YIG project are of high relevance for fundamental research but have no immediate application in the industrial use.

3) Qualification of Junior Researchers (max. 2 DIN A4 pages)

During the whole period of the YIG project, 3 post-doctoral researchers (including me), 2 DESY-fellows and 7 PhD students contributed to the group activities. 2 more DESY-fellows joint my group close to the official end of the group, keeping the strength of the group high beyond the end of the YIG.

After positive evaluation in 2012, I obtained a staff position at DESY and will continue to lead the analysis efforts in BSM searches of the CMS DESY group.
I am currently convening the CMS SUSY future analysis group (2013-2014). I will be interested to further work in convening positions at the CMS experiment once my future analyses convenership is finished.
At DESY, I am one of the organizers of the LHC Physics Discussion Forum, where on a monthly basis topics are discussed among the theorists and experimentalists from the CMS and ATLAS collaboration.

Dirk Krücker, who worked as postdoc in my group, is now employed by DESY in the IT division.

Altan Cakir, who worked as postdoc in my group, holds currently a DESY fellowship position until middle 2015 and is still working in the DESY SUSY group.

Matthias Stein has successfully defended his PhD thesis on the topic “Search for SUSY with Two Same-Sign Leptons with the CMS Detector”. After working six months at DESY as postdoc, he moved to industry.

Hannes Schettler has successfully defended his PhD thesis on the topic “The Event-Mixing Technique for Modeling the $t\bar{t}$ Background in a Search for Supersymmetry in the Di-Lepton Channel”. After working three months at the Hamburg University as postdoc, he moved to industry as well.

Niklas Pietsch is expected to hand in his thesis within a few weeks on the topic ”Search for Supersymmetry in Final States with a Single Lepton, B-Quark Jets, and Missing Transverse Energy at the CMS Experiment”.

Francesco Costanza is expected to hand in his thesis on search for top squarks with the 8 TeV data in the next few months.

Özgür Sahin, a PhD student who started in my group, successfully applied for the high-level Joachim-Hertz-Scholarship and will finish his thesis.

Artur Lobanov and Karim Trippkewitz have joined my group in 2013 and will finish their PhD based on analysis of the data that will be taken from 2015 onwards. Artur Lobanov has been working on the upgrade of the Hadronic Outer Calorimeter up to now and gained a lot of experience in hardware work, while Karim Trippkewitz is working on future analyses.

Two DESY fellows, who joined my group, Elias Ron and Dean Horton, have also now moved to industry.

Two DESY fellows have joined my group recently: Alexis Kalogeropoulos and Claudia Seitz will strengthen the group for the next three years.

From May 2014 to April 2015 a colleague from the Teheran University joins our group as a guest.

4) Public relations

The group is well represented in the physics community by more than five presentations per year by the group members at the international conferences and public seminars.
The group leader and one of the postdocs, Altan Cakir are also actively giving lectures at schools.
The ongoing activities of the group along with the group members, and the job announcements are highlighted on a dedicated web page of the group, which can be found here:
http://cms.desy.de/e53612/e90916/e115480/ (linked from the main CMS DESY webpage)

5) Networking

My partner university is the Hamburg University, where all students are graduating. During the renovation of the DESY main building my whole group was hosted by the Hamburg University on the DESY campus, and we established a close collaboration with common working meetings. In the last two years, due to work on different topics, the collaboration was not too close.
We also collaborate with colleagues from the Moscow State University. Vladimir Volkov and Galina Bogdanova visit DESY every few months and work on the slow control of the micro-TCA crates.
I newly established a collaboration with Batool Safarzadeh Samani from the Institute for Fundamental Research of the Teheran University, who joins us as guest for one year, after which we plan to continue the collaboration.

6) List of Publications

Major journal publications:

- S. Chatrchyan *et al.* (CMS Collaboration), “Search for supersymmetry in final states with a single lepton, b-quark jets, and missing transverse energy in proton-proton collisions at $\sqrt{s}$=7 TeV“, PRD 87, 052006 (2013).
- S. Chatrchyan *et al.* (CMS Collaboration), “Search for top-squark pair production in the single lepton final state in pp collisions at 8 TeV“, EPJC 73 (2013) 2677.
- I.-A. Melzer-Pellmann, P.Pralavorio, “Lessons for SUSY from the LHC after the first run”, EPJC74 (2014) 2801, http://arxiv.org/abs/1404.7191

Public results (not published in a journal):

- CMS Collaboration, “CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter”, CERN-LHCC-2012-015, CMS-TDR-010;
- CMS Collaboration: “CMS Technical Design Report for the Pixel Detector Upgrade”, CERN-LHCC-2012-016, CMS-TDR-011;
- Y. Gershtein *et al*., “New Particles Working Group Report of the Snowmass 2013 Community Summer Study”, http://arxiv.org/abs/1311.0299v1.
- D. Abbaneo et al.“ ECFA High Luminosity LHC Experiments Workshop: Physics and Technology Challenges”, Report submitted to ECFA, ECFA-13-284, https://cds.cern.ch/record/1631032/.

Preliminary public results:

- CMS Collaboration, „Search for Physics Beyond the Standard Model in Opposite-sign Dilepton Events in pp Collisions at s = 7 TeV“, CERN-PH-EP-2011-016;
- CMS Collaboration: Search for supersymmetry in events with a lepton and missing energy, PAS-SUS-11-015;
- CMS Collaboration: Search for new physics with same-sign isolated dilepton events with jets and missing energy, PAS-SUS-11-009;
- M. Berggren, A. Cakir, D. Krücker, J. List, A. Lobanov, I.-A. Melzer-Pellmann, “Non-Simplified SUSY: stau-Coannihilation at LHC and ILC”, http://arxiv.org/abs/1307.8076.

Conference contributions with proceedings:

- Matthias Stein, “Studies with an Energy Weighting Method for the Upgrade of the Hadronic Barrel Calorimeter of CMS”, Proceedings of the international conference “Lepton Photon 2009” (approved by CMS as CR-2010/028);
- Altan Cakir, “Searches for Supersymmetry with the CMS Experiment”, Proceedings of LOMONOSOV11: 15th Lomonosov Conference on Elementary Particle Physics, 18-24 Aug 2011, Moscow (Russian Federation), http://arxiv.org/abs/1111.4820;
- Altan Cakir, ”SUSY Searches with the CMS Detector”, published in Communications, Faculty of Sciences, University of Ankara, Series A2-A3: Physics, Engineering Physics, Electronic Engineering and Astronomy, 2011;
- Hannes Schettler, for the CMS Collaboration, “SUSY Searches with Leptons in the Final State at CMS”, Proceedings of PIC2011: XXXI Physics in collision, 28 Aug-1 Sep 2011, Vancouver, BC; http://arxiv.org/abs/1111.2256;
- Altan Cakir, “Searches for SUSY in events with third-generation particles at CMS”, Proceedings of ICHEP 2012, Melbourne, Australia, http://arxiv.org/abs/1211.6289;
- Altan Cakir, “Search for RP violating Supersymmetry”, EPS-HEP 2013 Stockholm, Sweden: PoS(EPS-HEP 2013)264, http://arxiv.org/abs/1310.3598.