Search for New Physics in Events with Jets and Missing Transverse Momentum at the CMS Experiment

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Abstract

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Kurzfassung

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1 Introduction

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2 Theoretical Background

2.1 The Standard Model of Particle Physics

2.1.1 Shortcomings of the Standard Model

2.2 Supersymmetry

2.2.1 Searches for Supersymmetry at Collider Experiments

3 Experimental Setup

In order to probe the various aspects of the well-established standard model or search for hints of new physics beyond the SM, particle physics experiments preferentially make use of powerful particle accelerators where particles of a certain type are collided in order to probe the constituents of matter and interactions between them. The analyses presented in this thesis are all performed in the context of the CMS experiment located at the Large Hadron Collider (LHC) at CERN near Geneva.
The first part of this chapter provides an introduction to the LHC. This is followed by an overview of the detector system of the CMS experiment. Afterwards the hitherto periods of collision data taking at the LHC are discussed together with an introduction to the generation of simulated events which are used in the analysis of real data events.

3.1 The Large Hadron Collider

The Large Hadron Collider [2,3] is a ring-accelerator designed to provide particle collisions of hadrons. It is built in the tunnel of the former LEP [4] collider 45 – 170 m below the ground and has a circumference of 26.7 km. The LHC is a particle-particle collider and thus composed of two rings with counter-rotating beams. The operation can be performed in different modes with either proton beams or heavy ions like e.g. lead [1].
In each beam, protons are grouped together in bunches and accelerated in two evacuated beam pipes using superconducting radio-frequency cavities. With a nominal bunch spacing of 25 ns the bunch revolution frequency is 40 MHz. Each of the 2808 individual bunches per beam contains at design conditions 1.15×10^{11} protons. In order to bend the beams around the LHC ring superconducting dipole magnets are used with an operation temperature of 1.9 K. They provide a magnetic field of up to 8.33 T while additional quadrupole and sextupole magnets are utilized to squeeze and focus the beams.
Before the protons are injected into the LHC they are already pre-accelerated in various smaller accelerators up to a beam energy of 450 GeV while passing through the injector chain Linac2 – Proton Synchrotron Booster (PSB) – Proton Synchrotron (PS) – Super Proton Synchrotron (SPS). An overview of the accelerator complex at CERN is given in Fig. 3.1.

The main goal of the LHC is to provide proton-proton collisions to the experiments with center of mass energies up to 14 TeV in order to explore physics processes at novel energy regimes. The expected number of events N for a certain type of process is given by the product of the specific cross section σ of that process and the integral $L = \int \mathcal{L}\, dt$ of the instantaneous luminosity $\mathcal{L}$ over time such that

$$N = \sigma \cdot L. \tag{3.1}$$

[1] All studies presented in this thesis are based on proton-proton collisions. Thus the operation with heavy ions is not discussed.

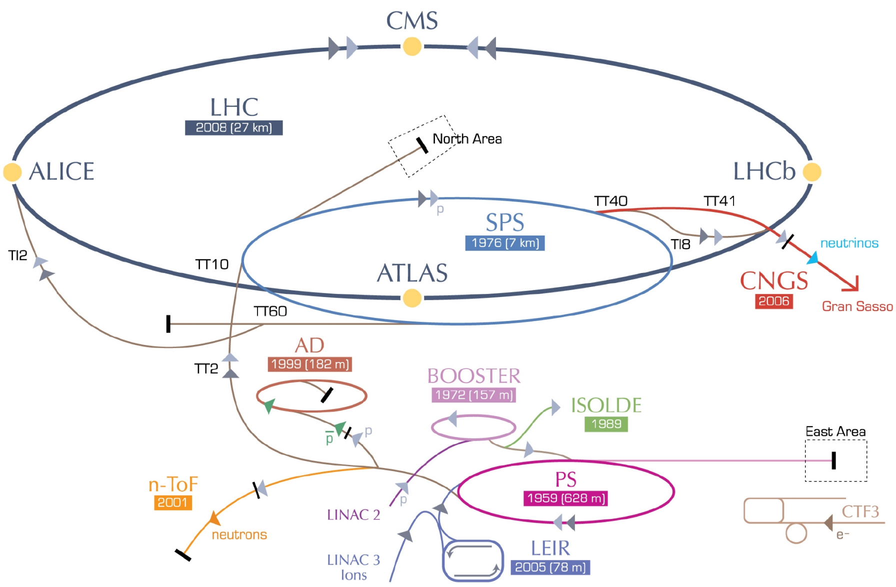

Figure 3.1: Illustration of the CERN accelerator complex. Numbers below the names of individual machines indicate the year of their first operation. For ring accelerators also the circumference is given. Taken from [5].

The luminosity is a machine parameter and can be expressed for beams with Gaussian-shaped profiles as

$$\mathcal{L} = f \cdot \frac{n_1 n_2}{4\pi\sigma_x\sigma y} \cdot F \tag{3.2}$$

with the revolution frequency f, the number of particles n_1 and n_2 contained in the two colliding bunches and the transverse beam sizes σ_x (σ_y) in the horizontal (vertical) directions. In order to take the inclination of the two beams into account, the geomatrical correction factor F is introduced. The nominal peak luminosity of the LHC is $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
The LHC beams cross at four locations along the ring. At these interaction points the four main experiments of the LHC are located in order to measure the delivered particle collisions. The two high luminosity experiments ATLAS [6] and CMS [7,8] are designed for multiple purposes like precision measurements of SM quantities, search for the standard model Higgs Boson or searches for signals indicating new physics processes. The LHCb detector [9] however is a specialised experiment focusing on the measurement of CP violation in the interactions of hadrons containing b-quarks. The only experiment designed especially for the analysis of heavy ion collisions is the ALICE [10] detector with the main emphasis on the physics of strongly interacting matter at extreme energy densities like for instance quark-gluon plasma.

3.2 The CMS Experiment

The CMS detector is one of the two experiments at the LHC designed to address a multitude of physics questions. In addition to tests of the SM at the TeV scale, studies of the

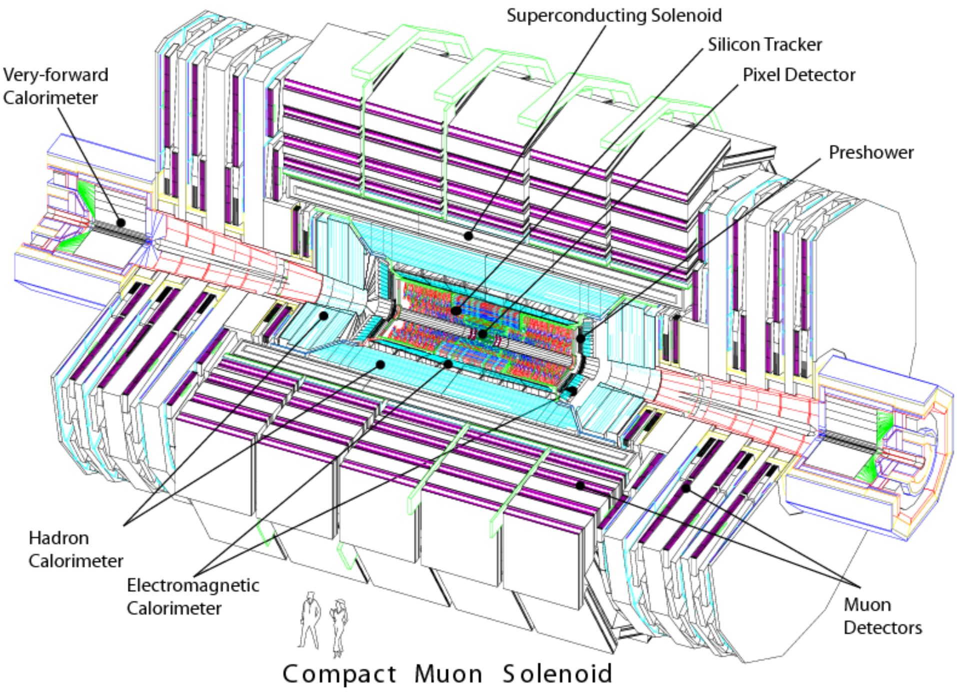

Figure 3.2: A perspective view of the CMS detector [7].

nature of elektroweak symmetry breaking which might show up in the presence of a Higgs boson and searches for so far unknown particles pointing to e.g. new symmetries in nature are the primary targets of these experiments. These ambitious physics goals can only be achieved by fully exploiting the by now unprecedented collision energy and luminosity. Since the total inelastic proton-proton cross-section at a center of mass energy of 14 TeV is expected to be around 100 mb , the experiments have to deal with an event rate of approximately 10^9 events per second. This is resulting in high experimental challenges. The CMS detector with its typical cylindrical design of different sub-detector components around the beam line is designed to perfectly meet these particular conditions. A sketch of the CMS detector and the different sub-detectors is shown in Fig. 3.2. As a typical high-energy particle experiment the CMS detector makes mainly use of tracking detectors and calorimeters to measure particles' momenta, energy depositions and flight directions in order to identify the objects emerging from the particle collisions. Table ... gives an overview of the performance goals of the various sub-detectors. The overall dimension of the CMS detector are a length of 21.6 m and a diameter of 14.6 m resulting in a total weight of 12500 t.

Bild + Ref

Performance Table

The following sections comprise a description of the CMS detector and individual sub-detector components focusing on the detector parts most relevant for the analyses presented in this thesis. A detailed discussion of the detector design can be found in [7, 8].

3.2.1 Coordinate Conventions and Kinematic Variables

In order to describe the particle collisions, the CMS experiment makes use of a right-handed coordinate system with its origin at the center of the detector at the nominal interaction point. While the z-axis is defined along the direction of the beam, the x-axis points to the center of the LHC ring and the y-axis vertically upwards. In this xy-plane the azimuthal angle ϕ is measured where $\phi = 0$ coincides with the x-axis. The polar angle θ however is defined with respect to the z-axis. A quantity closely related to the polar angle is the pseudorapidity η defined as

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{3.3}$$

which is widely used in experimental particle physics as rapidity differences are Lorentz invariant. A pseudorapidity $\eta = 0$ corresponds to the direction perpendicular to the beam while $|\eta| \to \infty$ points along the beam. Based on the pseudorapidity the Lorentz invariant distance between two objects $\Delta\mathrm{R}$ can be written as

$$\Delta\mathrm{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}\,. \tag{3.4}$$

At the LHC the initial conditions of the primary collisions are not known as the specific energy fraction of the proton which each parton carries can not be identified. Thus conservation of the total momentum can not be utilized directly to describe the momentum balance in the final state. However, it is known that the initial particles have no significant momentum orthogonal to the beam axis which is referred to as transverse momentum

$$p_\mathrm{T} = p \cdot \sin\theta\,. \tag{3.5}$$

Thus, momentum conservation in the transverse plane is used to describe the final state conditions. Any difference between the total sum of all transverse momenta and zero is considered as missing energy $\not{E}_\mathrm{T}$ and often exploited to describe undetected particles.

3.2.2 Superconducting Magnet

The CMS experiment makes use of a large superconducting solenoid magnet which is a crucial component of the whole detector design and provides a magnetic field of up to 4 T. It allows to precisely determine the momenta and charge of charged particles from the bended tracks that they follow in the magnetic field.

With a length of 12.5 m and a diameter of the free bore of 6.3 m the total cold mass reaches 220 t. It is made up of a niobium-titanium coil which is winded in 4-layers. This configuration allows a storage of 2.6 GJ energy at full current. A 10000 t heavy-weight iron yoke is responsible for the return of the magnetic flux.

3.2.3 Inner Tracking System

3.2.4 Electromagnetic Calorimeter

3.2.5 Hadronic Calorimeter

3.2.6 Muon System

3.2.7 Trigger System

3.3 Data Taking and Event Simulation

4 Reconstruction Algorithms and Object Definition

4.1 Global Event Description with the Particle-Flow Algorithm at CMS

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5.1 Basic Concept of the Dijet Asymmetry Method

5.2 Apllication to Realistic Collision Events

5.3 Samples and Event Selection

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5.3.2 Selection Criteria

5.4 Corrections to the Dijet Asymmetry

5.4.1 Correction for Additional Jet Activity

5.4.2 Correction for Particle-Level Imbalance

5.4.3 Results of the Corrections to the Asymmetry

5.5 Determination of the Data-to-Simulation Ratio of the Jet Transverse Momentum Resolution

5.6 Validation of the Method

5.6.1 Validation in Simulated Events

5.6.2 Validation of the Measured Data-to-Simulation Ratio

5.7 Systematic Uncertainties

5.8 Extension of the Method to the Forward Detector Region

5.9 Results

5.9.1 Comparison to Other Measurements

6 Search for New Physics in the Multijet and Missing Transverse Momentum Final State at $\sqrt{s} = 8$ TeV

6.1 Event Selection

6.1.1 Data samples and trigger

6.1.2 Event Cleaning

6.1.3 Baseline Selection

6.1.4 Exclusive Search Regions

6.2 QCD Background Estimation with the Rebalance-And-Smear Method

6.2.1 Rebalance Procedure using Kinematic Fits

6.2.2 Response Smearing

6.2.3 Validation Tests

6.2.4 Systematic Uncertainties

6.2.5 QCD Background Prediction

6.3 Estimation of Non-QCD Backgrounds

6.3.1 Invisible Z Background

6.3.2 Hadronic τ Background

6.3.3 Lost-Lepton Background

6.4 Results and Interpretation

7 Prospect Studies for a Search for Top Squarks in Events with Jets and Missing Transverse Momentum at $\sqrt{s} = 13$ TeV

7.1 Data samples

7.2 Top Tagging Efficiency Studies

7.2.1 Top Tag Efficiency

7.2.2 Misidentification Rate

7.3 Studies towards a Suitable Analysis Strategy

7.4 Results and Discussion

7.4.1 Comparison of the Performance of Various Selections

7.4.2 Discussion of Specific Simplified Assumptions in the Analysis

8 Conclusions

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