ETP-KA/2018-08

CMS-Experiment
Jet Rekonstruktion
Daten Simulation uebereinstimmung
Domain Adaptation

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MASTERARBEIT

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. . . .
(**Dr. Matthias Ulrich Mozer**)

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Karlsruhe, den 03. September 2017

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Deutsche Zusammenfassung

IEKP-KA/2017-02

CMS Experiment
jet reconstruction
Domain Adaptation

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MASTER THESIS

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Introduction

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Particle accelerator experiments have a great story of success in the investigation of physical laws. With these machines it was able to prove the existence of different elementary particles of the standard model. Particle accelerators use the electric charge of particles to accelerate them near to the speed of light. One kind of accelerator forces particles which move in opposite direction to collide at some point. The collision releases a high amount of energy and because of the laws of physics, heavy particles are produced which are highly unstable and decay after a short amount of time. To measure these particles, directly or indirectly, detectors are used.

This chapter gives a brief overview of the accelerator and detector system that has produced the events used in this work.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [32] **[?]** is a circular particle accelerator and located at the European Organization for Nuclear Research (CERN) in the region of Geneva. With a circumference of 27 km it is the world largest and most powerful particle accelerator and lies in a tunnel about 100 meters beneath the earth. The LHC is used to accelerate protons, xenon ions and lead ions. These particles undergo several steps of creation and pre-accelecation before they are injected in the LHC. An illustration of the system is shown in figure 2.1.
The LHC was constructed with two beam pipes, this allows the acceleration of protons in opposite direction. In this setup, for head on head collisions with equal beam energy, the center of mass energy is just twice the beam energy:

$$\sqrt{s} = 2 \cdot E \tag{2.1}$$

In 2010, the first collisions with a beam energy of 3.5 TeV and therefore $\sqrt{s} = 7\,\text{TeV}$ started. On this energy, the LHC was run until 2012 the center of mass energy was raised to $\sqrt{s} = 8\,\text{TeV}$. From 2013 to 2015 the LHC was shut down for maintenance. After this the run 2 started in 2015 with $\sqrt{s} = 13\,\text{TeV}$. After a shutdown in 2018, the LHC is planned to run on $\sqrt{s} = 14\,\text{TeV}$ in 2021 for run 3 (as of 2018).

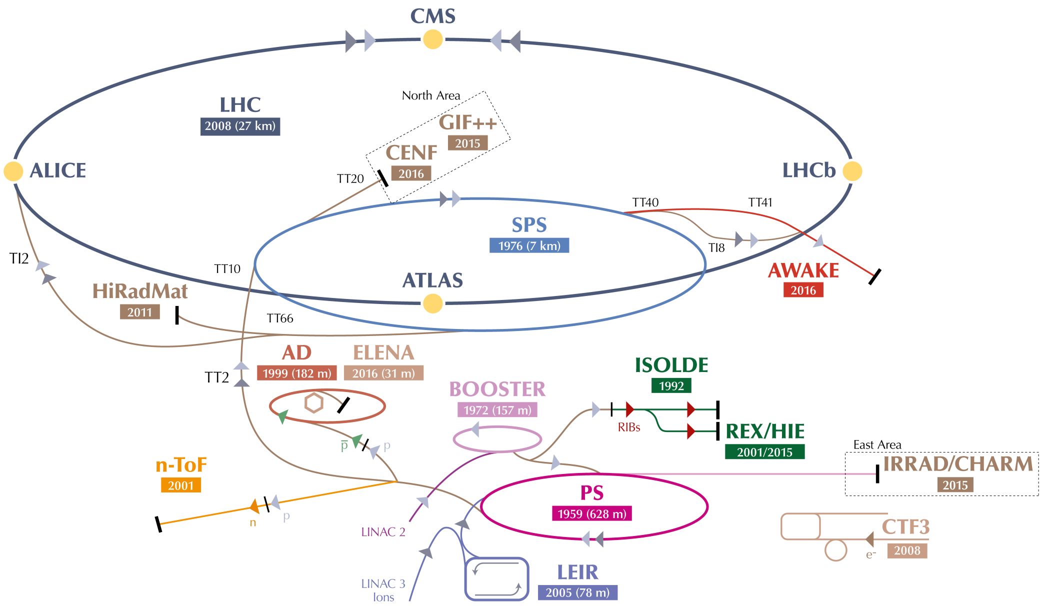

Figure 2.1: The CERN accelerator complex. The figure shows several accelerator facilities at CERN. The protons which end up in the LHC are obtained from hydrogen atoms and first accelerated with the LINAC2 to 50 MeV. Next they are injected into the Booster and accelerated to 1.4 GeV. It follows the acceleration of the Proton Synchrotron (PS) to 25 GeV and the Super Proton Synchrotron (SPS) to 450 GeV. Finally the protons are injected into the LHC in both directions. From there they reach a final energy of 6.5 TeV within 20 minutes. At the LHC the four main detectors are shown. Source: [?]

For run 2, the protons in the beam are packed in 2808 bunches, each bunch containing about $1.2 \cdot 10^{11}$ of them. For each beam, 8 superconducting cavities, cooled down to 4.5 K, generate an electromagnetic potential with a frequency of 400 MHz to accelerate and tighten the bunches. Each of the cavities is delivering 2 MV of energy. To avoid collisions with gas molecules during operation, the beam pipes have a ultrahigh vacuum pressure of 10^{-13} atm. 1232 dipole magnets with up to 7.74 T each, force the particle beam to stay on the circular path. Another 392 quadrupole magnets are used to focus the beam. To keep the magnets in an superconducting state, superfluid helium is used to cool them down to 1.9 K.
Besides the center of mass energy, the luminosity is another important quantity for particle accelerators. The luminosity L determines the event rate and therefore, a high Luminosity is desired:

$$\frac{dN}{dt} = \sigma L \tag{2.2}$$

Where σ is the cross section and is given by the physical laws. The luminosity is dependent of the properties of the particle accelerator:

$$L = \frac{nN_1N_2f}{A} \tag{2.3}$$

Where, n is the total number of bunches in the collider, N_1 and N_2 are the number of particles in the colliding bunches, f is the circulating frequency for one single bunch and A is the cross sectional area. On this formula you can see the importance of having a good focusing, that will shrink the A. To get the total number of events, one can integrate formula 2.1 over time to

$$N = \sigma \int L dt = \sigma L_{int} \tag{2.4}$$

Where L_{int} is the integrated luminosity. In 2017 a peak luminosity of $2.06 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ was reached with an integrated luminosity of $50\,\mathrm{fb^{-1}}$ ($1\,\mathrm{b} = 10^{-24}\,\mathrm{cm^2}$) for the total year [**?**]. After run 3 at the LHC, a high luminosity upgrade is planned to increase the luminosity to $5 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$.
The particle beams at the LHC are crossing at four different points, where at each point one detector is located. One is for the ALICE experiment which studies collisions of lead ions. Another one is for the LHCb experiment which is designed for the studies of b hadron physics. The ALICE and the CMS experiments are general purpose experiments for the measurement of the standard model particles and the search for new elementary particles.

2.2 The Compact Muon Solenoid Experiment

The Compact Muon Solenoid (CMS) detector was built up with the main motivation in the search for the higgs boson and the search for physics beyond the standard model. As

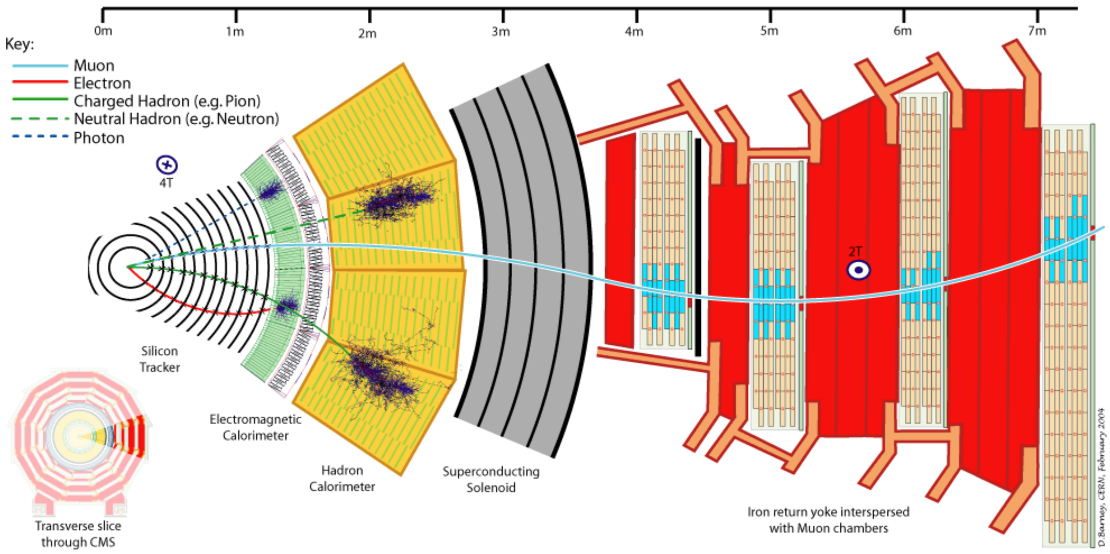

Figure 2.2: Slice of the CMS detector The scheme shows the different detector systems as well as some particle tracks and their interactions with the detector. Source: [40]

we know, the former has already been found, but we still search for alternative theories like supersymmetry or extra dimensions. Besides of those two big tasks, the CMS detector is used for a lot of other studies. For example the measurement of couplings of different particles [**?**]. In order to achieve these goals, the detector is required to measure the involved particles with best possible precision in position and energy. A sketch of a slice of the CMS detector with it's different layers is shown in figure **??**. The detector also needs a filter system, the so called trigger system, to store only the interesting events and reduce the amount of data to an amount that can be stored for further analysis. In this chapter, these systems are described shortly, in the following the typically used coordinate system is outlined.

coordinate system

The origin of the coordinate system is chosen to be the intended collision point. The z-axis points in the beam direction where the x lies in the plane of the collider ring and points to its center. The y axis points vertically upwards. The radial distance is $r = \sqrt{x^2 + y^2}$. ϕ is used as the azimuthal angle in the x-y plane measured from the x-axis. The polar angle θ is measured from the z-axis. Another important quantity is the pseudorapidity η. It is used to denote the angle between a vector and the z-axis:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{2.5}$$

A value of $\eta = 0$ is equal to $\theta = 90^\circ$, an angle of $\theta = 0^\circ$ equals $\eta = \infty$. It is preferred over θ since the number of produced particles per η interval is constant. Because the momentum and energy of the initial colliding particles is not determined in a hadron collider, most of the time only the transversal quantities to the beam axis are of interest. These quantities are invariant under lorentz boosts in z-direction and therefore be used. They are given as $p_T = \sqrt{p_x^2 + p_y^2}$ and $E_T = \sqrt{E_x^2 + E_y^2}$ respectively. All transverse momentum and energy should sum up to one, in the measurement. The missing amount is denoted as p_T^{miss} and E_T^{miss}.

Silicon Tracker

The most interesting things in particle physics happen immediately after the collision. Heavy objects decay in less then nanoseconds and with sufficient effort some can be reconstructed. The innermost part of the detector is therefore of highest importance and has several requirements to fulfill. First, a good measurement of trajectories of charged particles is necessary to identify primary and secondary vertices. This also allows a momentum measurement as the full tracker is inside the CMS solenoid. This solenoid produces a homogeneous magnetic field of 4 T. Next, at each bunch crossing, in average about 1000 particles are created and travel through the detector. To distinguish the particles from each other and to assign the trajectories to the corresponding vertices, a high granularity is needed. Further, the time between two bunch crossings is about 25 ns therefore the response time and the cooling down period has to be short. Last but no least, the detector components have to be resilient against this high amount of radiation.

To fulfill these requirements, silicon technology is used for the whole tracker system. When charged particles travel through this materials, electron-hole pairs are produced, which in turn generates an electric current in the read out electronics. In the innermost part from r =4.4 cm to 10.2 cm, three barrel layers of pixel detectors are surrounding the beam axis. Each pixel detector has a size of $100 \times 150\,\mu\text{m}^2$. With this design, the occupancy for each pixel and bunch crossing is of the order of 10^{-4}. The pixel detectors are surrounded by 10 layers of silicon micro-strip detectors up to a radius of 1.1 m. As the particle flow decreases with the radius, larger detector elements can be used. This also reduces the amount of read out electronics. The inner micro strip detectors have a size of $10\,\text{cm} \times 80\,\mu\text{m}$ where the size of the outer once is $25\,\text{cm} \times 180\,\mu\text{m}$. At the endcaps, 2 disks of pixel detectors and 3 smaller and 9 larger discs of strip detectors are installed. This allows a reconstruction of charged particle tracks up to $|(\eta)| < 2.5$. In total the silicon tracker has a lenght of 5.8 m with a diameter of 2.5 m. At each bunch crossing, the occupancy of the detectors is at about 2-3 % for the inner micro strip detectors and lower for the other once. For high energetic muons (100 GeV), the resolution for the impact parameter, which is the distance of a reconstructed track from a vertex, is about 10 μm.

Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) surrounds the silicon tracker system hermetically and measures the energy of electrons, positrons and photons. Other electromagnetic interacting particles leave tracks but are not fully absorbed in the ECAL. The ECAL consists of homogeneous lead tungstate ($PbWO_4$) crystals which is the absorber and scintillator material at the same time. When electromagnetically interacting particles propagate through it, they produce photons through bremsstrahlung, which in turn create electron-positron pairs through pair production. An electromagnetic shower emerges. When the energy of the electrons drops to a critical amount, they mainly excite the atoms which emit photons with characteristic wavelength (scintillation). These photons are then measured with photomultiplier. The number of photons is proportional to the deposited energy of the particle. The radiation length of $PbWO_4$ is $X_0 = 0.89\,\text{cm}$. This means that after this distance, the energy of an electron or positron reduced by the factor of $1/e$. The thickness of the ECAL with 23 cm is equivalent to 25.8 X_0, therefore all electrons positrons and photons are absorbed completely. The ECAL at the CMS was build with the main motivation for a good measurement of the $H \rightarrow \gamma\gamma$ channel. Therefore it has a good energy resolution. To reduce the background in this channel, a preshower detector is installed just before the ECAL. This element helps to identify neutral pions that decay into two photons, it also impoves the position determination of electrons, positrons and photons.

Hadronic Calorimeter

Hadrons propagate through the ECAL with loosing only small parts of their energy, therefore an hadronic calorimeter (HCAL) is surrounding the ECAL which absorbs all hadrons and measures their energy. Therefore it's important for measuring hadron jets as well as the total energy of the system and the resulting missing transverse energy. Several elements allow to measure forward jets up to $|\eta| = 5.2$.

The HCAL at CMS is a sampling calorimeter which exists of alternating absorbing layers and scintillating layers. The absorbing layer, the so called brass, consists in main parts of copper and tin. The brass has a nuclear interaction length of $\lambda_I = 16.42\,\text{cm}$. This is the mean distance for a hadronic particle after which it undergoes an inelastic nuclear interaction. Similar to the ecal, a chain reaction starts and an hadronic shower emerges. The total absorber material ECAL and HCAL makes up almost 7 λ_I and is therefore sufficient to absorb all hadrons. For the scintillating layers, plastic is used. When the hadronic shower hits these layers, the scintillator material gets excited. Photons with characteristic wavelength are emitted. They are guided through optical cables and measured by photodiodes.

Muon Detector

The muon detector is the part furthest from the collision point. The only particles that reach this part of the detector are neutrinos, which can not be detected with the CMS detector, and muons. Muons have a high mass and often high energy. Because of this, they loose only few energy by propagating through the inner parts and are usually not totally absorbed in the muon detector either. Muon identification and position determination is done with gaseous detectors. As they pass through these detectors, muons are ionizing the gas atoms, the resulting electrons and ions can then be measured as en electric current. The muon system consists of a iron return joke to guide the magnetic field lines of the solenoid through this part of the detector. This creates a magnetic field of 2 T. As a consequence, muons travel a circular path. The momentum can then be determined by measuring the radius.

Trigger System

The LHC has a pp interaction rate of more then 1 GHz at each crossing point. This results in too much data to store every event. Anyway only in small parts, interesting physic processes occur. To reduce the event rate to a storable amount by selecting only interesting events, a trigger system consisting of two steps is used at the CMS [**?**]. The first selection is called the Level-1 (L1) trigger and is realized by hardware electronics. It has to decide in 4 μs if the event is worth to keep. In this short time only parts of information from the calorimeters and the muon chamber can be used. The L1 trigger decides if the information is consistent with a physics objects like an electron, muon or others. At the end the event rate is reduced to less then 100 MHz.
The second trigger selection step is done by the High-Level Trigger (HLT). The HLT is realized with software tools where complex calculations and a more precise reconstruction can be done. Further is the information of the tracking system now included. This selection reduces the event rate further to an average of 400 Hz. These events are then stored offline for further analysis.

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