ETH ZÜRICH

DOCTORAL THESIS

Same-sign dileptons as a search tool at CMS

Author:
Marc Dünser

Supervisor:
Prof. Dr. Rainer Wallny

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D-PHYS

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Declaration of Authorship

I, Marc Dünser, declare that this thesis titled, 'Same-sign dileptons as a search tool at CMS' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.
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"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

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Abstract

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Doctor of Science

Same-sign dileptons as a search tool at CMS

by Marc Dünser

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too…

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor...

For/Dedicated to/To my…

Contents

Chapter 1

Introduction

The construction of the Large Hadron Collider (LHC) and its experiments at CERN in Geneva over the few last decades has been just the last step in a long and successful history of particle accelerators that started roughly 100 years ago. Just as the first specimens of its kind, the LHC serves – first and foremost – the purpose of fundamental research. It has been conceived in order to answer some of the most fundamental questions of modern day physics, such as *'how do particles acquire mass?'* or *'what is dark matter?'*. Despite the purely scientific origin of these questions and the improbability of any 'practical' application from any possible answer to them, it is important to note that fundamental research in general and the research at the LHC in particular do serve a greater and more applicable purpose.

The invention of the world wide web and HTML FIXME(CITE), early developments on touch screens, research on medical physics with high-power magnet systems as well as medical imaging and the use of high energy ion beams for tumor treatment are only a few examples of the direct consequences on daily life which fundamental research on particle physics entails.

This thesis is dedicated almost exclusively to data analysis of high-energy particle collisions which took place in the CMS experiment at the LHC. By looking at such collisions, the aforementioned question about the origin of mass has already been answered FIXME(CITE) with the discovery of the Higgs boson in 2012 by both the CMS and ATLAS collaborations. The second question, however, remains unanswered and the work presented in the following is largely devoted to a search for particles which could provide physicists with a suitable candidate for a dark-matter particle.

Chapter 2 describes the fundamentals of particle physics from a theoretical standpoint, Chapter FIXME will provide on overview of the CMS experiment. Chapters FIXME to FIXME will then describe the search for new physics etc. blabla.

Chapter 2

Theory

In order to interpret any experimental result, it is of paramount importance to understand the underlying model governing the physical processes in question. Modern physics knows a large number of rather successful theories all dedicated to describing different mass and energy scales. An example is the theory of classical mechanics, which manages to describe the physics of 'daily life' very well. However, it breaks down when velocities approach the speed of light and has to be incorporated into a broader theory, namely that of relativity.

This specific example already suggests that different physical theories are valid only in a certain energy range and describe only a certain 'type'[1] of physical process. This fact is also true for the case of particle physics. The relevant theory is called the *'Standard Model'* and will be described hereafter. Further into the chapter, a short description of the pitfalls of the standard model will be given with some explanation on possible solutions.

2.1 The Standard Model

The Standard Model (SM) of particle physics provides the theoretical framework that describes all fundamental particles and the forces that act between them, with the one exception of gravity. Despite a few drawbacks that will be described later (see Section 2.1.2) it has been an overwhelmingly successful theory, capable of describing experimental data with a precision that is simply outstanding.

[1]In this particular example electromagnetic interactions are – for instance – not described at all.

2.1.1 Particle content in the Standard Model

2.1.2 Shortcomings of the Standard Model

2.2 Supersymmetry

2.2.1 Particle content

2.2.2 Observables for searches for Supersymmetry

2.3 Remaining open questions in particle physics

Chapter 3

Experimental Setup

All data analysed in this thesis was recorded with the CMS experiment at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland. This chapter provides a short overview of CERN and its accelerators, the LHC, as well as a short description of the main components of the CMS experiment.

3.1 The Large Hadron Collider

The LHC [1] is currently by far the largest and most powerful particle accelerator in the world. It is a circular accelerator situated in a tunnel around 100 metres below the Swiss-French border west of Geneva. Its main purpose is accelerating protons to energies of up to 13 TeV [1] in the final development stage of the machine starting in 2015. Besides the acceleration of protons it is also capable of accelerating heavy ions (predominantly lead ions) to energies of up to 2.76 TeV per nucleon.

3.1.1 The acceleration chain

Particles injected into the LHC for final acceleration are required to have an energy of 450 GeV. This is achieved by a long chain of linear and circular accelerators, a sketch of which can be seen in Fig. 3.1.

Protons used for acceleration in the LHC are extracted from a hydrogen molecules in a bottle situated at the CERN main site. These molecules are stripped of their electrons

[1]One electronvolt (eV) is the energy acquired by a charge of $1e$ passing through an electric field of 1 volt, equivalent to 1.602×10^{-19} Joule.

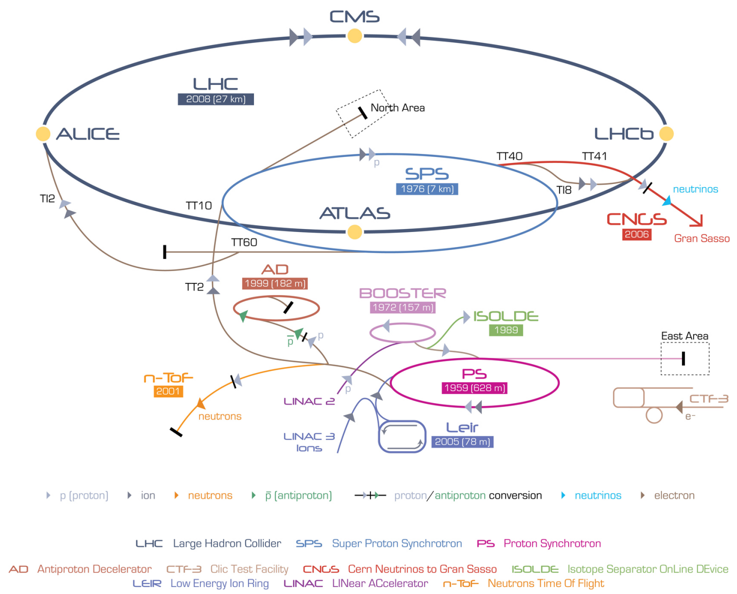

FIGURE 3.1: Conceptual drawing of all accelerators and experiments hosted at CERN. Besides operating the LHC, there are many other accelerators, decelerators and experiments being operated.

by strong electric fields and subsequently injected into the first acceleration stage, the linear accelerator Linac 2. Upon exiting Linac 2, the protons have gained an energy of 50 MeV and are injected into the first circular accelerator, the Booster. This synchrotron with a circumference of 157 meters accelerates the protons to an energy of 1.4 GeV and uses magnetic dipole fields to bend the protons onto a circular path. These bending magnets are operated at room temperature for the Booster and in fact all the accelerators up to the LHC. From the Booster, the protons are injected further into the Proton Synchrotron, an accelerator originally built in 1959 with a circumference of 628 meters and an output energy of 25 GeV. The last step before injection into the LHC is the Super Proton Synchrotron (SPS), which accelerates the protons to the LHC injection energy of 450 GeV. The SPS is the world's second largest accelerator with a circumference of nearly 7 km, and it was the first accelerator to collide protons and anti-protons at energies high enough to produce W and Z bosons, leading to their discovery in 1983 [2, 3].

Ions pass through the same accelerators on their way to the LHC with the notable exception of the very first acceleration being done in Linac 3 rather than Linac 2.

While the LHC is filled and delivering collisions to its experiments, the accelerators are used to provide particles to other experiments ongoing at CERN. The Antiproton Decelerator (AD) in which anti-protons are decelerated and combined with positrons to form anti-hydrogen, and the ISOLDE collaboration for the study of many different radioactive ions are just some of the examples of interesting experiments ongoing at CERN.

3.1.2 Specifications of the LHC

The LHC itself is located in a tunnel roughly 50-150 meters below ground in the Geneva area, extending from Lake Geneva all the way to the Jura mountain chain. Its total circumference is 26 659 meters which makes it – together with its predecessor the Large Electron Positron Collider hosted in the same tunnel – by far the largest particle accelerator ever built. It is divided into 8 sectors, separated and named by the eight access points to the tunnel. A schematic drawing of the LHC with all its access points can be found in Fig. 3.2. Access points 1, 2, 5, and 8 host the four main experiments ATLAS, ALICE, CMS, and LHCb, the acceleration is performed by radio-frequency (RF) cavities at point 4, the beam-dump system is located at point 6 and beam monitoring and conditioning is performed at points 3 and 7 [4].

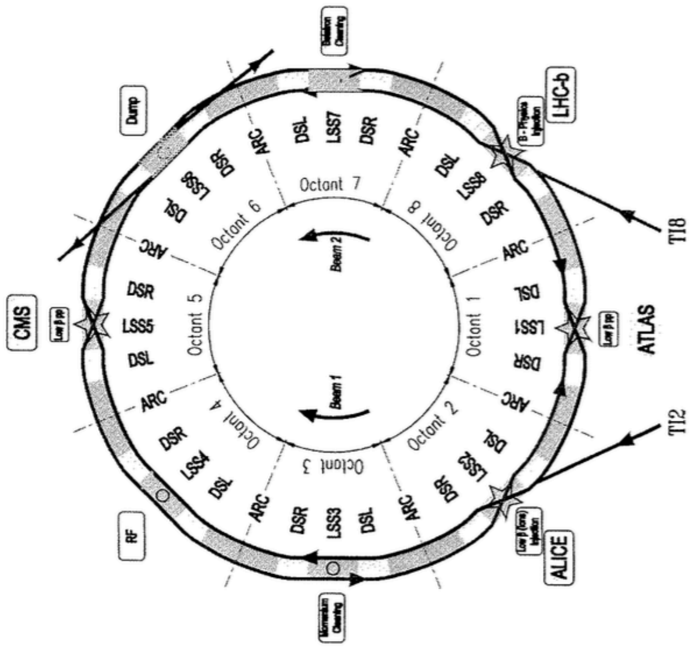

FIGURE 3.2: Schematic drawing of the LHC ring and its sectors and access points numbered in clockwise direction starting at the ATLAS experiment in point 1.

The magnet system

Particles are injected from the SPS into the LHC into two counter-rotating beams in discrete bunches at the aforementioned 450 GeV. In order to control the particles on their circular path, an intricate magnet system was designed in order to bend and to focus the beams. The main feature of the LHC magnet system are the 1232 dipole bending magnets, each roughly 15 meters in length and weighing 30 tonnes. These magnets are made of a niobium-titanium alloy, a type-2 superconductor which allows current transport without loss at the operating temperature of 1.9 K. Cooling of the LHC cold mass of roughly 37 Mt is achieved with pressurized superfluid helium. Each magnet hosts two separate beam-pipes for beam 1 (clockwise) and beam 2 (counter-clockwise) with the dipole magnetic field pointing in opposite direction in either of them. In order to achieve acceptable beam lifetimes and to minimize beam-gas interactions, the beam pipes are evacuated and the residual gas pressure is around 10^{-10} mbar. Upon injection from the SPS the dipole magnets are operated at a magnetic field strength of 0.535 T which is slowly raised during the acceleration period of the beam to a final field strength of 8.33 T at the maximum collision energy.

Alongside the dipole magnets for the bending of the particles, there are thousands of additional magnets for correcting and controlling the particle's path. The largest part of the correction magnets are sextupole magnets situated on either side of every dipole magnet. Further components include a decapole and an octupole corrector for each dipole magnet as well as injection kicker magnets and kicker magnets for the beam dump system among others.

The RF cavities

Once the LHC is filled and circulation of the beams is stable, they are accelerated from their initial energy by the means of so-called RF cavities which provide a high frequency alternating electric field of nominally 400.8 MHz. Similar to the bending magnets, the RF cavities are operated in a superconducting state at a temperature of 1.9 K. There are a total of eight such cavities per beam, each achieving a potential difference of 2 MV for a combined 16 MV necessary for acceleration at collision energy. During the acceleration period of the beams, the energy gain per particle per turn is 485 keV with the total power consumption of the RF system being around 275 kW.

Beam parameters

In order to measure the performance of a particle accelerator such as the LHC, the quantities of instantaneous and integrated luminosity are the most important figure of merit, as they correspond to the total number of particle collisions produced in any given collision point. The instantaneous luminosity is defined as

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F, \tag{3.1}$$

where N_b denotes the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency of each bunch, γ_r the relativistic gamma factor, ϵ_n the normalized beam emittance, β^* the β-function of the beam at the collision point, and F a geometrical factor inversely proportional to the crossing angle of the two beams at the interaction point.

The beam emittance is defined as the volume of the beam in the position-momentum phase space and is thus a measure of the quality of the beam. Emittance itself is inversely proportional to the beam momentum and it is therefore necessary to introduce a normalized emittance, which does not change its value with momentum in order to compare beam quality before and after acceleration. The β-function describes the behavior of the transverse beam size as a function of the position in the accelerator, and the value β^* is consequently proportional to the transverse size of the beam at the collision point.

The dimension of the instantaneous luminosity is $cm^{-2}s^{-1}$ and by integrating it over time the integrated luminosity $\mathcal{L}_{int}$ is obtained. Through knowledge of the latter, one can calculate the total number of expected events for any given physical process in a data sample of a given size by

$$N_{\text{process}} = \mathcal{L}_{int} \cdot \sigma_{\text{process}}. \tag{3.2}$$

All relevant beam parameters to calculate the instantaneous luminosity at the LHC are summarized in Table 3.1 at both injection and collision energies.

Performance of the LHC

All values in Table 3.1 refer to the design values of the LHC, while the actual performance since startup in 2008 has been considerably different. After the initial startup in the autumn of 2008 when beams were first injected into the machine, a faulty connector

TABLE 3.1: Beam parameters for beams in the LHC at injection and collision energy.

Beam parameters

	Unit	Injection	Collision
Beam Energy	[GeV]	450	3500 - 7000
Relativistic γ_r		479.6	3730-7461
Particles per bunch		1.15×10^{11}	
No. of bunches		2808	
f_{rev}	[Hz]		11245
ϵ_n	[μm rad]	3.5	3.75
Half crossing angle[2]	[μrad]	$\pm$ 160	$\pm$ 142.5
β^*	[m]	18	0.55

between superconductors caused a significant explosion in the cooling system of the main magnets, resulting in a shutdown and repair period until late 2009. However, upon restarting of the machine in 2009, operations of the LHC have been almost flawless, with many parameters of the LHC reaching or even exceeding their design targets. Since the limiting factor for the LHC energy is the attainable magnetic field strength in the bending magnet, combined with safety concerns regarding the replaced connectors from the incident in 2008, a staged approach for a slow energy ramp-up was implemented for the LHC. First stable collisions for data-taking in 2010 were performed at an energy per proton of 3.5 TeV resulting in 7 TeV center-of-mass energy. This energy was maintained also during 2011 before being increased to 8 TeV in center-of-mass energy during the 2012 data-taking period. This thesis focuses on the dataset at 8 TeV. The energy will further be increased to 13 TeV in center-of-mass in early 2015.

Regarding the luminosity, the LHC has outperformed its early expectations. Despite the fact that so far only half the bunches were filled, resulting in a bunch spacing of 50 ns instead of the design 25 ns, the maximum instantaneous luminosity has almost reached its design value of 1×10^{34} $cm^{-2}s^{-1}$ in late 2012, when an LHC fill with an instantaneous luminosity of 7.67×10^{33} $cm^{-2}s^{-1}$ was recorded. This was mostly due to the increase in protons per bunch.

3.2 The CMS experiment

As briefly mentioned before, the LHC provides high energy particle collisions to four large particle physics experiments, namely the ALICE, ATLAS, CMS, and LHCb experiments. While the ALICE and LHCb experiments are specially designed for specific purposes, the study of heavy ion collisions and the study of processes involving the b-quark, respectively, the ATLAS and CMS experiments are design as ‘general purpose’ experiments. As such, their goal is the detailed scrutiny of the SM, the search for the recently observed Higgs boson [FIXME - reference], and the search for new physics phenomena. They do this by means of measuring and absorbing decay products of the collisions. The relevant physical observables of any particle produced in a particle collisions are the momentum vector and the energy of a particle. Once these two quantities are known, every particle can be identified unambiguously.

Data collected for this thesis were recorded by the CMS experiment.

3.2.1 General structure and the magnet

The Compact Muon Solenoid (CMS) experiment is located roughly 100 meters below ground in Cessy, France, it is cylindrically shaped with dimensions of roughly 22 meters in length and a diameter of about 16 meters. A drawing of the CMS detector is shown in Fig. 3.3.

The convention for the coordinate system is as follows. The origin of the coordinate system is at the nominal interaction point. The x-axis points towards the center of the LHC ring, the y-axis points towards the surface and the z-axis points towards the west, along beam 2. The azimuthal angle ϕ is measured in the x-y plane, while the polar angle θ is measured from the positive z-direction. It is commonly replaced by a quantity called pseudo-rapidity defined as $\eta = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$.

The whole apparatus comprises a barrel part in the center and a so-called endcap on either side to seal the detector as hermetically as possible.

As the presence of the word 'solenoid' in the acronym for CMS already suggests, its main feature is a very large, solenoid magnet which defines the overall structure of the experiment. Much like the LHC bending magnets, it is a superconducting structure and the conducting material is a niobium-titanium alloy, albeit at a very different scale. It measures roughly six meters in inner diameter and 13 meters in length, carrying a current of about 18 000 (FIXME) ampere, resulting in a maximum magnetic field strength of 3.8 T [5]. In addition to the actual magnet, the CMS magnet system also comprises a return yoke for the magnetic field lines to be homogeneous as a function of the distance from the interaction point. Altogether, the magnet system weighs approximately 11 000 metric tons, by far the heaviest component of the CMS detector. As momentum resolution of charged particles is a critical factor in the physics performance of a detector, the magnetic field strength within the tracking volume is desired to be as large as possible.

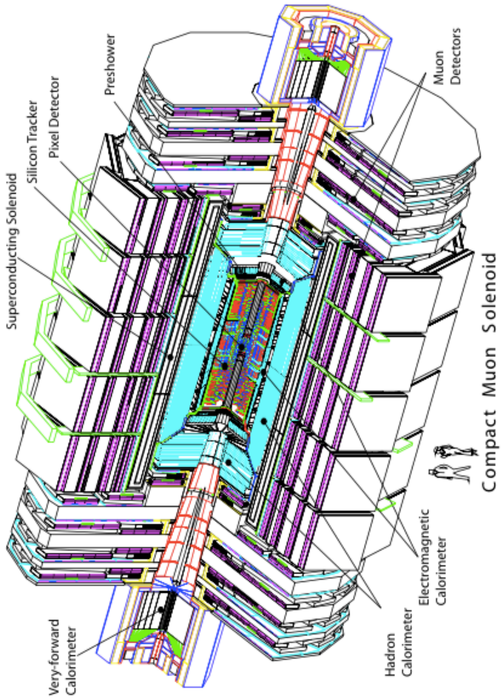

FIGURE 3.3: Perspective view of the CMS detector. The cylindrical shape as well as the barrel and endcap geometry can be clearly seen. The depicted people are to scale [4].

The large volume of the CMS magnet allows for most subdetectors to be situated within a very high magnetic field. Not only the tracking detectors, but also the calorimetry for energy measurement are fully incorporated within the magnet's volume.

3.2.2 The subdetectors

To get the most information out of a particle collision, a particle detector should be as hermetic as possible. Naturally, a perfectly hermetic detector is unattainable, and a cylindrical shape is the compromise most particle detector designs have adapted. Full coverage in azimuthal angle is comparatively easily obtained, and the coverage in polar angle is only limited by the length of detector volume. Instead of measuring coordinates

3.2.3 The trigger system

3.2.4 Reconstruction and data formats

3.2.5 Monte-Carlo simulation

Appendix A

Dummy Appendix

You can defer lengthy calculations that would otherwise only interrupt the flow of your thesis to an appendix.

List of Figures

List of Tables

Abbreviations

LAH **L**ist **A**bbreviations **H**ere

Physical Constants

Speed of Light $c = 2.997\,924\,58 \times 10^{8}\ \mathrm{ms}^{-\mathrm{S}}$ (exact)

Symbols

a	distance	m
P	power	W (Js^{-1})
ω	angular frequency	$rads^{-1}$

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