ETH ZÜRICH

DOCTORAL THESIS

Same-sign dileptons as a search tool at CMS

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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.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- 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…

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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 XXX) 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.

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.

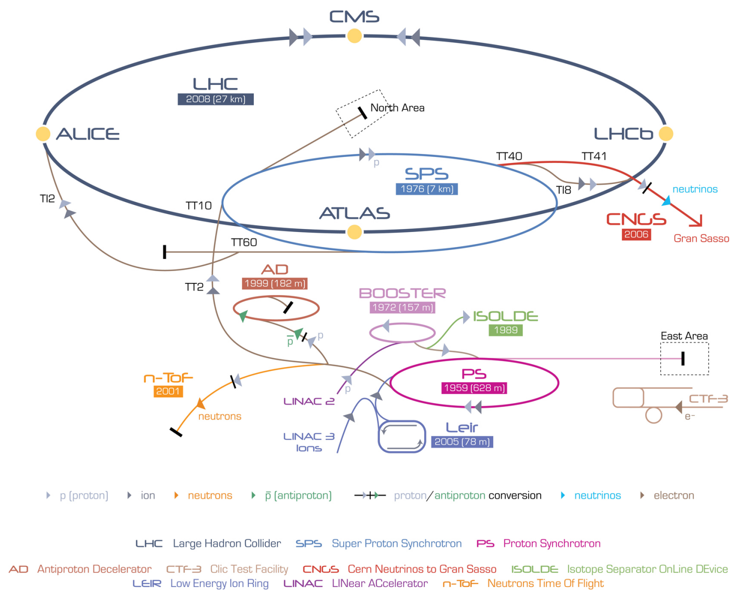

FIGURE 3.1: Conceptual drawing of all accelerators and experiments hosted at CERN. Besides operating the LHC, there are many other accelerators, decelerators and experiments being operated.

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, the only difference being the first linear accelerator, which in the case of heavy ions is Linac 3.

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 50-150 meters below ground and has a total circumference of 26 659 meters. Particles are injected from the SPS into the LHC into two counter-rotating beams at the aforementioned injection energy of 450 GeV.

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, 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 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 $m^{-2}s^{-1}$ and by integrating the instantaneous luminosity over time the integrated luminosity $\mathfrak{L}_{int}$ can be 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

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

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

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

		Injection	Collision
Beam parameters			
Beam Energy	[GeV]	450	3500 - 6500
Relativistic γ_r		479.6	xxxx-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

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

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Abbreviations

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

Physical Constants

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

Symbols

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

Bibliography

[1] Oliver Sim Brüning, Paul Collier, P Lebrun, Stephen Myers, Ranko Ostojic, John Poole, and Paul Proudlock. *LHC Design Report*. CERN, Geneva, 2004.

[2] The UA1 collaboration. *Experimental observation of isolated large transverse energy electrons with associated missing energy at s=540 GeV*. *Physics Letters B*, 122(1):103 – 116, 1983. ISSN 0370-2693. doi: http://dx.doi.org/10.1016/0370-2693(83)91177-2. URL http://www.sciencedirect.com/science/article/pii/0370269383911772.

[3] The UA1 collaboration. *Experimental observation of lepton pairs of invariant mass around 95 GeV/c^2 at the CERN SPS collider*. *Physics Letters B*, 126(5):398 – 410, 1983. ISSN 0370-2693. doi: http://dx.doi.org/10.1016/0370-2693(83)90188-0. URL http://www.sciencedirect.com/science/article/pii/0370269383901880.