

# Engineering and Computational Techniques of Particle Detection Utilized in the Compact Muon Solenoid

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## 1 Introduction

On July 4th 2012, CERN hosted a press conference to announce their findings from the Large Hadron Collider (LHC) [1]. While the world waited with baited breath, CERN researchers confirmed they had identified a particle with mass 125 GeV [2]. This discovery implied the existence of the Higgs boson, a particle that has been postulated to exist for at least 60 years [3].

The LHC utilizes two complementary general-purpose detectors: ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). The two detectors work independently of one another, and in the case of the Higgs particle, provide independent verification of discovery [4]. In this paper, we present a small portion of the data presented by the CMS collaboration that supports the existence of a Higgs boson with mass 125 GeV. We will then explore the engineering strategies of the CMS detector that enabled this unique discovery, and the computational techniques used to validate the possible existence of the Higgs.

## 2 CMS Collaboration Results

### 2.1 Interpreting CMS Data

The existence of the Higgs boson can not be detected directly, rather it is identified through its decay products [5]. These decay products are not only produced in the Higgs decay, but are created through the decay of other particles. The decay products produced in reactions of previously discovered particles are known as the “background” and the search for the Higgs must show that the rates of the pertinent decays are significantly higher than the background rates of decay.

The CMS collaboration selected five of the most sensitive decay modes in the low-mass region ( $m_H = 110 - 160$  GeV, where  $m_H$  is the invariant mass of the Higgs boson) their search for

the Higgs. Two decay modes provided high mass resolution:  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4\ell$ ; while three other modes only provided low mass resolution:  $H \rightarrow WW \rightarrow 2\ell 2\nu$ ;  $H \rightarrow \tau\tau$ ; and  $H \rightarrow b\bar{b}$ . The  $ZZ$  and  $\gamma\gamma$  modes are important because they provide an excellent resolution (1-2 GeV) of the invariant mass of the decay products, and consequently give the best estimate for the value of the Higgs' mass [2]. For the remainder of this paper we will be exploring the CMS collaboration's analysis of the  $H \rightarrow ZZ$  decay mode, and specific technical information as to how their result was calculated.

## 2.2 The $H \rightarrow ZZ$ Decay Mode

The Higgs has two fully leptonic decay modes

$$H \rightarrow WW \rightarrow \ell^+ \nu \ell^- \bar{\nu} \quad (1)$$

and

$$H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^- \quad (2)$$

where

$$\ell = [e \text{ (electron)}, \mu \text{ (muon)}] \quad \text{and} \quad \nu = (\text{neutrino})$$

The decay mode (2) is known as the ‘golden’ channel for discovery. This is due to the fact that the entire decay chain can be fully reconstructed with high resolution [6] because the invariant mass of the electron and muon decay products are easily resolved by the CMS detector [7]. The high resolution of the golden channel compared to other decay modes comes with a price: the branching ratio of the  $Z \rightarrow \ell^+ \ell^-$  is only 3.37%, so only 0.5% of the Higgs bosons which decay via the  $ZZ$  channel will decay further into the golden channel[6]. Furthermore, the background signals from quark-antiquark and gluon-gluon processes produce topologically similar events, obscuring possible Higgs detections [2].

The data we will be discussing is provided in Figure 1, which depicts the evidence supporting a Higgs boson with mass of 125 GeV via the  $ZZ$  channel. Figure 1 shows both the complete dataset and a reduced dataset with the background signal suppressed. The CMS collaboration utilizes several techniques to minimize the contribution of the background signals. Other than the irreducible quark-antiquark and gluon-gluon processes, there are several background signals that can be minimized[2]:

$$Z + b\bar{b}, \quad (3)$$

$$Z + t\bar{t}, \quad (4)$$

$$Z + \text{jets}, \quad (5)$$

$$\text{and} \quad WZ + \text{jets}. \quad (6)$$

The strategies for eliminating these background processes will be further discussed in Section 4.

The invariant masses of the lepton products is determined using relativistic kinematics. The

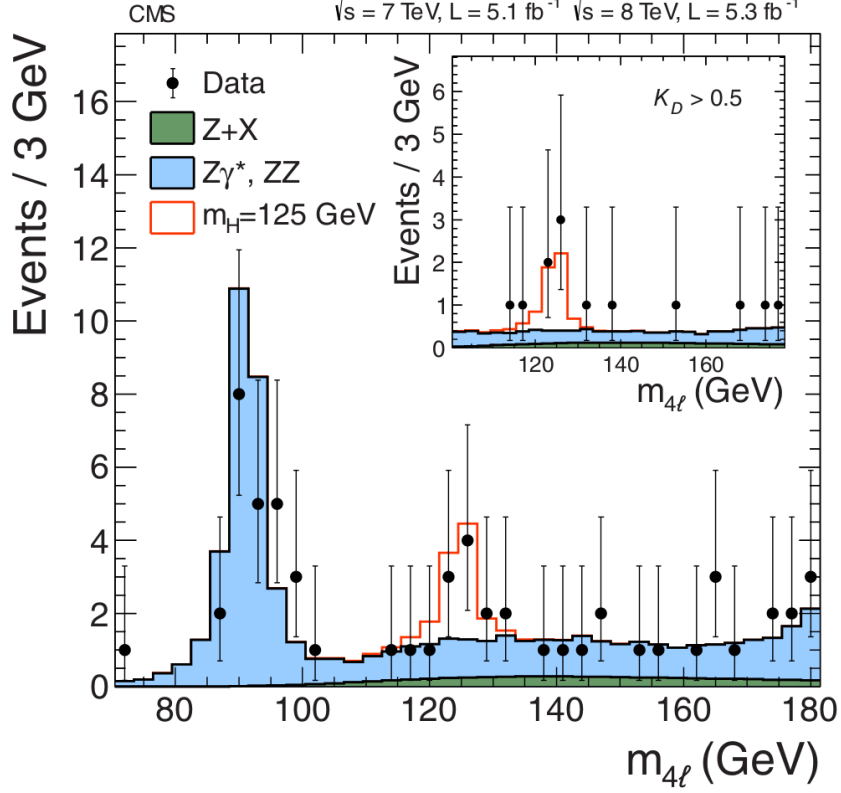


Figure 1: Distribution depicting the four-lepton invariant mass for the CMS collaboration’s  $ZZ \rightarrow 4\ell$  analysis. The points represent data gathered by the CMS experiment, the filled histograms represent the predicted four-lepton background signal, and the red histogram represents the predicted four-lepton signal for the Higgs boson with a mass of 125 GeV. The inset distribution represents the same plot after the background events have been minimized.

kinematics of the  $H \rightarrow ZZ \rightarrow 4\ell$  system can be solved completely in the rest frame of the Higgs using only seven parameters: the invariant masses of the lepton pairs and five angles [2], known as Cabibbo-Maksymowicz (CM) angles[8]. These angles are defined in Table 1 and Figure 2. It is interesting to note that the CMS collaboration did not consider the momentum of the  $ZZ$  system, due to the dependence on the production mechanism and the additional complications of modeling the QCD effects[2].

Angle	Description
$\Theta$	The polar angle of the initial-state partons (gluons, quarks) in the H rest frame. Measured from the positive z axis (along the anti-clockwise beam direction)
$\theta_1$	The polar decay angle of the $\ell_1^-$ in the $Z_1$ rest frame.
$\phi_1$	The azimuthal decay angle of the $\ell_1^-$ in the $Z_1$ rest frame.
$\theta_2$	The polar decay angle of the $\ell_2^-$ in the $Z_2$ rest frame.
$\phi_2$	The azimuthal decay angle of the $\ell_2^-$ in the $Z_2$ rest frame.

Table 1: The five Cabibbo-Maksymowicz angles in the  $H \rightarrow ZZ$  decay mode, and their definitions [8].

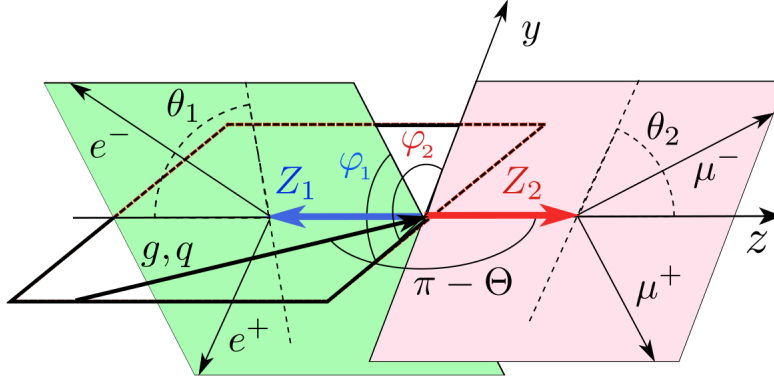


Figure 2: Visual description of the Cabibbo-Maksymowicz angles in the  $H \rightarrow ZZ$  decay mode [8].

Armed with an understanding of the parameters associated with identifying the Higgs boson via the  $H \rightarrow ZZ \rightarrow 4\ell$  decay mode, we can now explore the design of the CMS experiment and identify what techniques are used to capture this data.

### 3 Design of the Compact Muon Solenoid

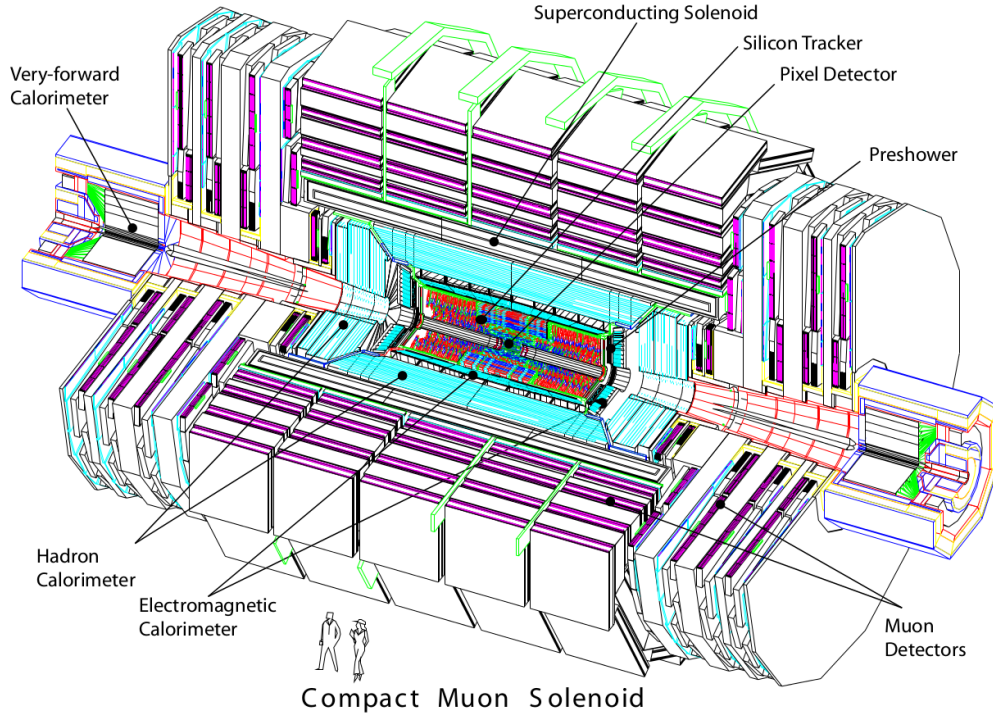


Figure 3: A cut-away perspective view of the CMS experiment, with each of the major sensors within the experiment identified [9].

### 3.1 Overview

The CMS experiment is designed to identify approximately 1000 charged particles emerging from the interaction region every 25ns. To ensure that the products of a single interaction are interpreted separately and that two subsequent interaction events don't get confused with one another, the experiment must use high-granularity detectors with good time resolution. This results in a large number of detector channels with very low occupancy, which produce an unprecedented amount of data. With these challenges in mind, the requirements of the experiment are as follows:

- Good muon identification and momentum resolution, with the ability to determine the charge of the muon.
- Good charged-particle momentum resolution.
- Good electromagnetic energy resolution, with the ability to isolate photons and leptons.
- Good missing-transverse-energy and dijet-mass resolution.

The heart of the CMS experiment is the superconducting solenoid, which is sandwiched between the calorimeters on the interior of the experiment, and the muon detectors on the exterior[9]. The solenoid provides a substantial magnetic field of 4T which is used to determine the momentum of charged particles and muons [10].

For analyzing the trajectories of leptons produced in the golden decay channel, data from nearly all of the sensors in the CMS experiment must be employed[11].

### 3.2 Tracker

### 3.3 Electromagnetic Calorimeter

### 3.4 Muon Detectors

## 4 Computational Techniques

### 4.1 CMS Software Architecture

### 4.2 Event Filter

### 4.3 Detector Description

### 4.4 Simulation

### 4.5 $H \rightarrow 4\ell$ Analysis Code

## 5 Conclusion

## References

- [1] CERN. Press conference: Update on the search for the Higgs boson at CERN on 4 July 2012. <http://indico.cern.ch/event/196564/#>, June 2012.
- [2] The CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716(1):30–61, January 2013. <http://arxiv.org/pdf/1207.7235v2.pdf>.
- [3] P.W. Higgs. Broken symmetries, massless particles and gauge fields. *Physics Letters*, 12(2):132–133, September 1964. [http://ac.els-cdn.com.proxybz.lib.montana.edu/0031916364911369/1-s2.0-0031916364911369-main.pdf?\\_tid=421a6d50-e092-11e4-9fae-00000aabb0f6b&acdnat=1428788130\\_f08d5fb23e00c9c41da7bcc724435630](http://ac.els-cdn.com.proxybz.lib.montana.edu/0031916364911369/1-s2.0-0031916364911369-main.pdf?_tid=421a6d50-e092-11e4-9fae-00000aabb0f6b&acdnat=1428788130_f08d5fb23e00c9c41da7bcc724435630).
- [4] LHC Higgs Combination Group. Procedure for the LHC Higgs boson search combination in Summer 2011. Technical report, CERN, August 2011. [http://cds.cern.ch/record/1379837/files/NOTE2011\\_005.pdf](http://cds.cern.ch/record/1379837/files/NOTE2011_005.pdf).
- [5] J.F. Gunion, G.L. Kane, and Jose Wudka. Search techniques for charged and neutral intermediate-mass Higgs bosons. *Nuclear Physics B*, 299(2):231–278, 1988. <http://deepblue.lib.umich.edu/bitstream/handle/2027.42/27338/0000363.pdf?sequence=1&isAllowed=y>.
- [6] Dr. Francesco Pandolfi. *Search for the Standar Model Higgs Boson in the  $H \rightarrow ZZ \rightarrow \ell^+\ell^-q\bar{q}$* . PhD thesis, Sapienza Università di Roma, Rome, Italy, 2013. <http://download-v2.springer.com.proxybz.lib.montana.edu/>

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- [7] J.S. Gainer, K. Kumar, I. Low, and R. Vega-Morales. Improving the sensitivity of Higgs boson searches in the golden channel. *Journal of High Energy Physics*, 2011(11), November 2011. <http://arxiv.org/pdf/1108.2274v2.pdf>.
- [8] A. De Rújula, Joseph Lykken, Maurizio Pierini, Christopher Rogan, and Maria Spiropulu. Higgs boson look-alikes at the LHC. *Phys. Rev. D*, 82(1):013003, Jul 2010. <http://link.aps.org/doi/10.1103/PhysRevD.82.013003>.
- [9] CMS Collaboration. The CMS experiment at the CERN LHC. *Journal of Instrumentation*, 3(08), August 2008. <http://stacks.iop.org/1748-0221/3/i=08/a=S08004>.
- [10] T.S. Virdee. Physics requirements for the design of the ATLAS and CMS experiments at the Large Hadron Collider. *Philosophical Transactions of the Royal Society*, 370:876–891, 2012. <http://rsta.royalsocietypublishing.org/content/roypta/370/1961/876.full.pdf>.
- [11] CMS Collaboration. CMS physics technical design report. Technical report, CERN, February 2006. <http://cds.cern.ch/record/922757/files/lhcc-2006-001.pdf>.

## 6 Questions for first draft

1. Should the sources be organized in the order they were cited, or by author’s last name?
2. In this paper, particles are identified in italics because L<sup>A</sup>T<sub>E</sub>X automatically italicizes characters in math mode. Is this standard notation, or should I make an effort to unitalicize particle symbols?
3. I feel as if I am following the CMS collaborations paper, ”Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC” too closely, as I have to cite it often. Is this inappropriate for this assignment? Is there a slight modification I can make to my topic to ensure that I don’t just restate the work of the CMS collaboration, or is such a situation unavoidable when doing a research paper such as this?
4. Is it proper to cite source code in this context? I’m not quite sure I want to do that yet, but do you have any experience in these matters?

## 7 Other Remarks

1. For convenience, a copy of all the sources I cited is available at [https://github.com/byrdie/PHSX\\_451\\_final\\_paper/tree/master/sources](https://github.com/byrdie/PHSX_451_final_paper/tree/master/sources)

2. Please let me know if I am straying too far into Jackson Remington's territory on this project. I have been communicating with him, and it seems that he is focusing more on the theoretical side. If you find that our topics are overlapping by too much I would be happy to modify my paper to avoid redundancy.