Observation of a New Particle in the Search for the Standard Model Higgs Boson at the CMS Detector

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Abstract

The discovery of the Standard Model (SM) Higgs boson is one of the primary physics objectives of the Large Hadron Collider at CERN. This thesis describes a search carried out for the SM Higgs boson on data collected during the 2011 and 2012 proton-proton (pp) collision runs with the CMS detector corresponding to integrated luminosities of $5.1 fb^{-1}$ and $5.3 fb^{-1}$ respectively. A detailed description of the search for the SM Higgs boson decaying to two photons from the full dataset collected at CMS during the 2011 pp collision run is provided. In particular, the development of signal and background modelling techniques used for statistical interpretations of the data are highlighted. Results of the search using these techniques from the 2011 dataset are presented. In addition, an update to the analysis including data taken during 2012 is described and the results from the combined 2011 and 2012 analyses given. Results from the combination of several Higgs decay channels at CMS are reported, including those presented in the International Conference on High Energy Physics in July 2012 at which the announcement of discovery was made. Ongoing studies to ascertain the properties of the new particle are discussed and preliminary results from the combined 7 and 8 TeV datasets (corresponding to $5.1 fb^{-1}$ and $12.2 fb^{-1}$ respectively) are presented.

Declaration

I, the author of this thesis, hereby declare the work contained in this document to be my own. Studies conducted and results produced by the author are indicated in the main body of text. All figures labelled "CMS" are sourced directly from CMS publications, including those produced by the author and have, been referenced as such in the figure caption. Where the figure is sourced from a CMS document which is unpublished or from a preliminary public document (marked "CMS Preliminary"), a reference to that document is included. All figures and studies taken from external sources are referenced appropriately throughout this document.

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"*Un bon mot ne prouve rien.*"

— François-Marie Arouet (Voltaire)

Chapter 1.

The LHC and CMS experiment

1.1. The Large Hardon Collider

The LHC is a 27km circular circumference storage ring, accelerator and collider for both protons and Pb ions. It is situated in a stable environment in a tunnel 100 metres underneath the Franco-Swiss boder near Geneva, Switzerland. A double-ring synchotron, it is designed to collide proton-proton (p-p) pairs with a centre of mass energy of up to $\sqrt(s) = 14$TeV and a luminosity of up to $10^{34} cm^{-2} s^{-1}$. This makes the LHC the only collider in operation able to directly probe the TeV scale physics.

The injected beams in the LHC are accelerated and stored for each physics run using a $400MHz$ superconducting cavity system. The beams of protons or pB ions are merged at four sections around the ring to enable collisions at interaction points. At each of these four interaction points lies one of the four main experiments at the LHC; A Large Ion Collidor Experiment (ALICE) [1], A Toroidal LHC Apparatus (ATLAS) [2], the Compact Muon solinoid (CMS) [3] and LHCb which record the collisions. Figure **??** shows the layout of the LHC ring including the positions of the four main detectors. The proton beams are made up of many 'bunches' of approximately 1.1×10^{11} protons localised into less than 1 ns in the direction of motion. The beams are formed inside the Proton Synchrotron (PS) from bunches of protons 25 or 50 ns apart with an energy of 26 GeV. The protons are then accelerated in the Super Proton Synchrotron (SPS) to 450 GeV before being injected into the LHC at the points shown in Figure **??**. Once injected into the LHC, Radio Frequency (RF) cavities provide around 275kW of RF power independently to each beam to accelerate the protons to allow collisions at the operating centre of mass energy. For the work contained in the thesis $\sqrt(s) = 13$TeV with

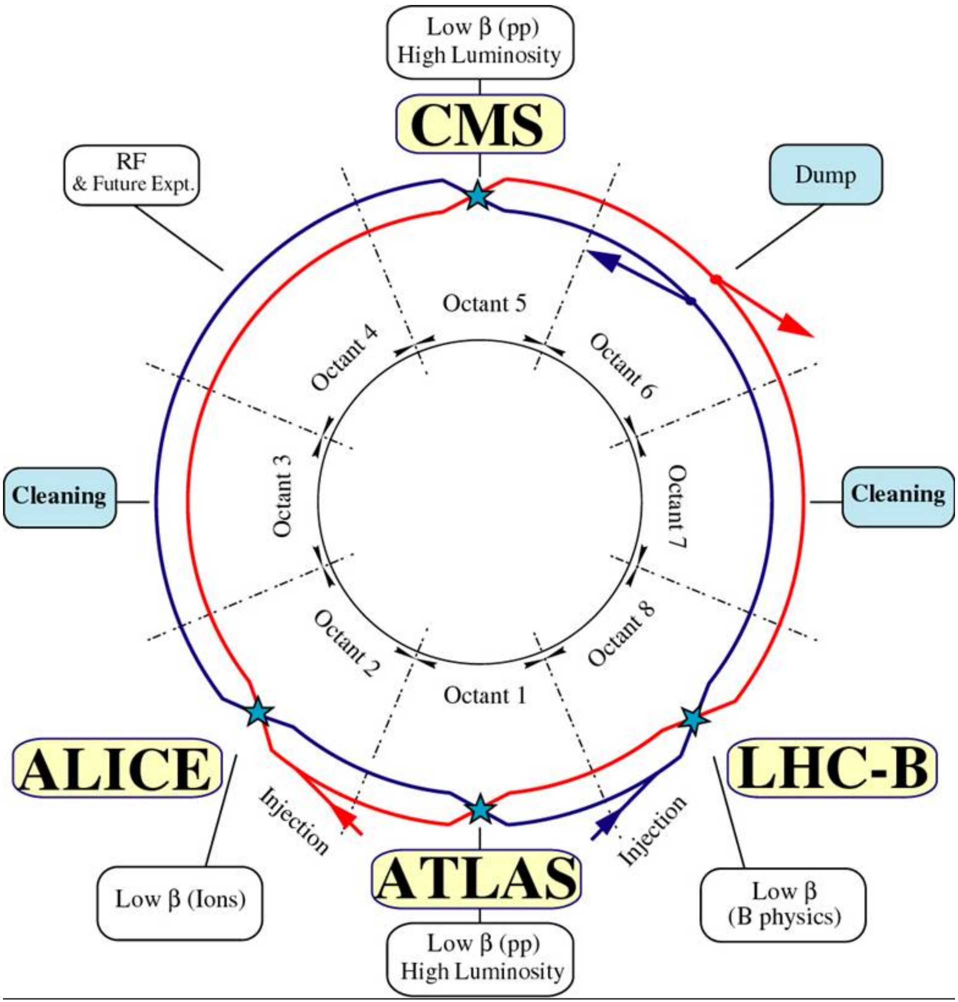

Figure 1.1.: Schematic layout of the LHC showing the position of the four main detectors as well as the RF systems

bunch spacings of both 25ns and 50 ns [4]. The LHC operates as a storage ring for the accelerated beams using 1232 superconducting dipole magnets in the eight arc segments which provide magnetic fields of up to $8T$ to steer the beams. High precision quadropole and higher order magnets at the interacton points are used to position and focus the beams to maximise the occurance of high momentum p-p collisions. The average number of simultaneous collisions per bunch crossing, in time pile-up (PU), for the work in this thesis was ≈ 25. The luminosity in the LHC is not constant over a physics run, but decays due to the degradation of intensities and emittances of the circulating beams (mainly due to loss from collisions). Eventually, the beam is dumped and the acceleration process is started again. The turn around time between dumping the beam and the start of a new physics run is typically around 6 hours.

1.1.1. LHC run conditions

The first physics runs of the LHC from 2010-2013 (Run 1) reached energies of 3.5 and 4 TeV per beam and provided record-breaking integrated luminosities. The data collected allowed for the discovery of the higgs boson[**?**] as well as enabling many new regions of parameter space to be probed. From 2013 to mid-2015 (Long Shutdown 1) the LHC was shut down for upgrade to allow design energies to be reached. All magnet interconnectors were inspected and replaced where necessary and the dipole magnets underwent a quench training programme.

After LS1, from 2015-2016 (Run 2, which will continue up to 2018) the LHC has been running with record beam energies of 6.5TeV per beam with bunch spacings of 25 and 50 ns. As shown in Figure 1.2, in 2016, $40.7fb^{-1}$ of integrated luminosity has been delivered to the CMS and ATLAS detectors, with $37.5fb^{-1}$ recorded by CMS. This dataset has enabled large areas of parameter space to be probed and limits to be set on new physics models. It is this XX/fb dataset, at a centre of mass energy of $\sqrt{(s)} = 13$TeV, which is used in Chapters XX to search for Supersymmetry at the highest energy ever reached at a collider.

1.2. The CMS detector

The Compact Muon Solenoid (CMS [3]) is one of two general purpose detectors at the LHC which have performed exceptionally well during the physics runs of the LHC. It was designed with the aim of discovering the Higgs boson as well as searching for generic models of new physics. To achieve this, CMS provides efficient identification and measurement of physics objects including muons, electrons, photons, taus and hadronic showers over a wide range of momenta and energies and covering almost 4π in solid angle. Its traditional barrel design allows global momentum imbalance to be effectively reconstructed allowing the $E_{\mathrm{T}}^{\mathrm{miss}}$ predicted in many new models of physics to be precisely measured. A more detailed description may be found in [3].

A cross section of CMS is shown in figure 1.3. The coordinate system used by CMS takes the origin at the collision point. The z-axis points along the beam direction and defines the azimuthal angle, ϕ. Instead of the polar angle, θ, the psuedorapidity, $\eta = -ln(tan(\theta/2))$, is used as $\Delta\eta$ between two particles is approximately relativistically invariant. The eta coverage of CMS is $|\eta| < 5$. Transverse energies and momenta (E_T

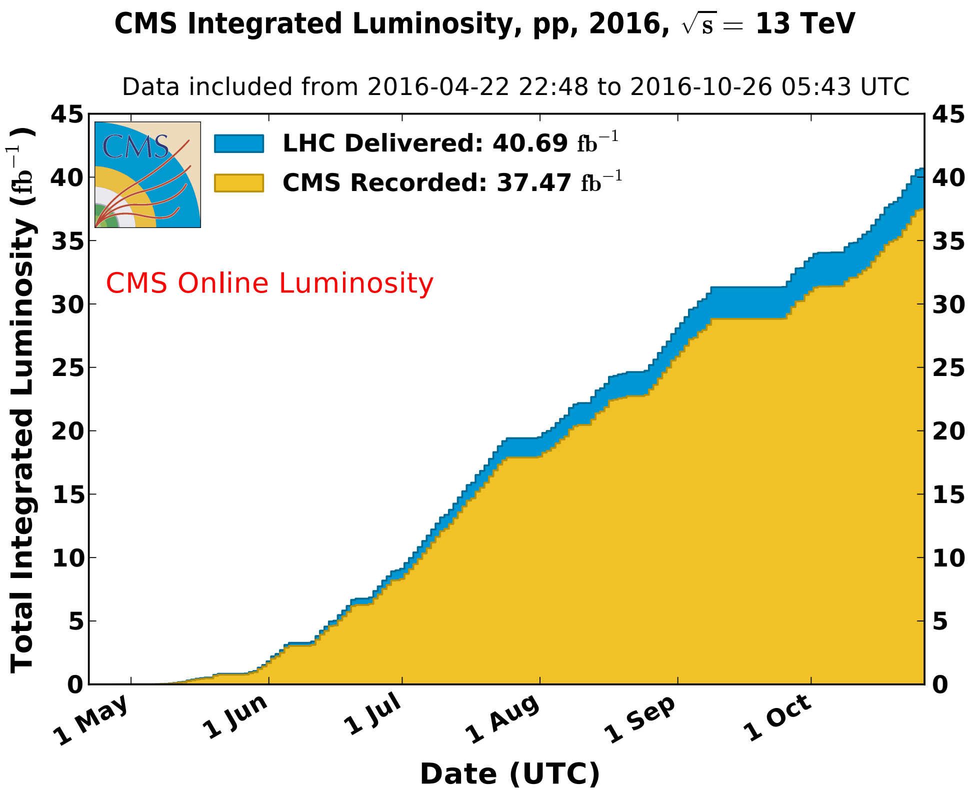

Figure 1.2.: Integrated luminosity measured online versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for p-p collisions at 13 TeV centre-of-mass energy in 2016.

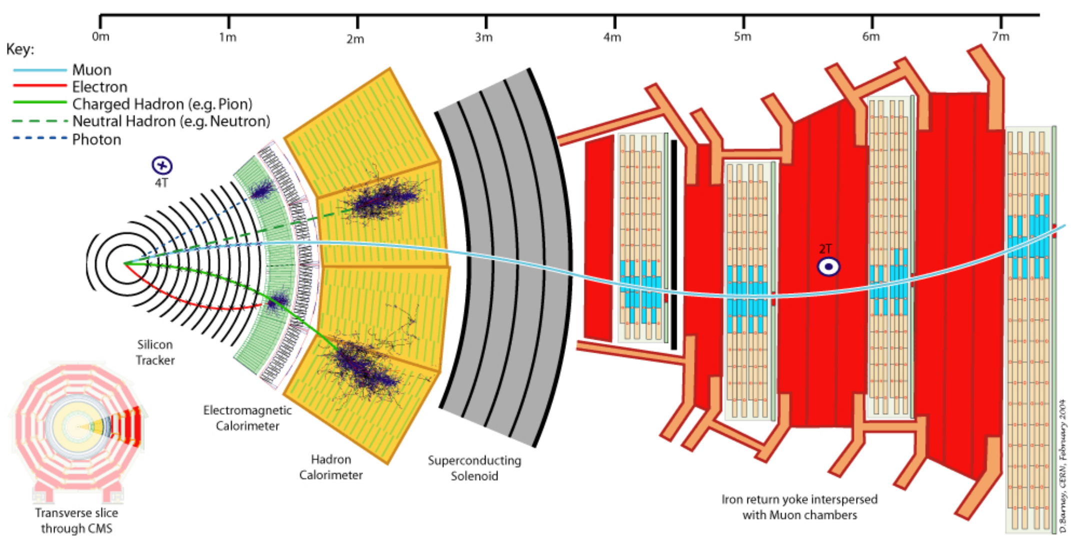

Figure 1.3.: Cross Section of CMS showing the paths of various particle types through different segments of the detector [5]

and p_T) are defined perpendicular to the beam [?]. The different detector components shown in figure 1.3 will now be described in detail. Resolutions are quoted for measuring the relevant property for a 100 GeV particle/jet [?].

Silicon Tracker The job of the tracker is to measure the momentum of charged particles from their path through a magnetic field [?]. The CMS tracker achieves $10\mu m$ accuracy with coverage for $|\eta| < 2.5$ and has a resolution of 1%.

Electromagnetic Calorimeter (ECAL) The ECAL measures the energy of incident photons and electrons. The ECAL barrel is made of 61,200 $PbWO_4$ crystals and provides coverage for $|\eta| < 1.48$ [?]. This is extended to $|\eta| < 3$ by the endcap which adds another 10764 crystals. The endcap has a pre-shower to distinguish between γ and π^0. The ECAL has a resolution of 0.5%.

Hadronic Calorimeter (HCAL) The HCAL is made from alternating brass and scintilator layers with a coverage of $|\eta| < 3.0$ [?]. The coverage is extended to $|\eta| < 5.0$ by an iron/quartz forward calorimeter [?]. The average resolution is 11%.

Muon Chambers The muons are not stopped by any of the calorimeters and therefore require a separate detector with coverage $|\eta| < 2.4$. The muon chambers are interspersed with the magnet return yoke. The high magnetic field allows for accurate momentum measurement [?]. The resolution is 1%.

As the data rate ($40Mhz$) is far too high for every event to be stored and as new physics will only be seen in a minority of events a trigger system for interesting events is necessary. This happens in two stages: the L1 Calorimetric and Muon Trigger (Hardware) and the High Level Trigger (Software) [?]. The L1 trigger must operate within $\mathcal{O}10ns$ and so the calorimetric trigger only takes input from the ECAL and HCAL. This is described in more detail in chapter **??**. The input from the L1 triggers is then combined in the Global Trigger (GT) which decides whether to keep the event. The $\mathcal{O}100kHz$ events which pass L1 selection are processed in the HLT which utilises the calorimeter information along with tracking and the muon system to further reduce the rate to $\mathcal{O}1kHz$.

Appendix A.

Appendix

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