Honors Thesis

March 3, 2013

Search for the Standard Model Higgs boson in the $H \to Z\gamma$ decay mode with pp collisions at $\sqrt{s} = 7$ and 8 TeV

Joshua Loyal[a]

[a]*Duke University, Physics Department*

Abstract

The ATLAS and CMS collaborations have observed a Higgs-like boson with a measured mass of 125.2 ± 0.3 (*stat*) $\pm$ 0.6 (*sys*) GeV using data taken from the Large Hadron Collider (LHC) in Geneva, Switzerland. Now it is important to understand the various properties of the Higgs-like resonance using all of the available information provided by the ATLAS experiment. As such, a search for the Standard Model Higgs boson in the decay channel $H \to Z\gamma$, $Z \to \ell^+\ell^-$, where $\ell = e$ or μ, was conducted using proton-proton collisions recorded with the ATLAS detector at the LHC. The distribution of the difference Δm between the final state three-body mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ is compared to Standard Model (SM) background expectations. No significant deviation from the SM prediciton is observed and upper limits on the cross-section of a Standard Model Higgs boson with a mass between 120 and 150 GeV are derived. The expected exclusion limits at 95% confidence level range between 7.3 and 22 times the predicted Standard Model cross section. The observed exclusion limits range between 5.4 and 37 times the Standard Model cross section. For a Higgs boson mass of 125 GeV, the expected and observed limits are 13.5 and 18.2 times the Standard Model, respectively.

Contents

1 Introduction

Elementary particle physics addresses the question, 'What is the world made of?' at the most fundamental level, i.e. on the smallest scale of size. One could easily imagine a world where the elementary building blocks of nature come in a vast variety of shapes and sizes. Just think of the multitude of parts that work together to make up an ordinary car. Remarkably this is not the case. The tiniest chunks of nature come in a small number of different types (electrons, quarks, photons, and so on), which are replicated in astronomical quantities to form our macroscopic world. However, this is not the whole story. Not only is elementary particle physics concerned with identifying the various fundamental actors of nature, but also how these actors interact amongst each other. It is during this investigation that the familiar forces of nature make their appearance. This paper is concerned with measuring both of these phenomena through the search for a new particle known as the Higgs boson as well as observing how this particle interacts with two other important actors: the photon and the Z boson.

The current answer to the question of what the world is made of is displayed in Figure 1 and is known as the Standard Model. This table is reminiscent of the periodic table developed by chemists to explain the various atoms found in nature. A surprising property of the Standard Model is that it consists of only 16 different particles. There are six quarks, shown in purple, which are the building blocks of the familiar nucleons, i.e. the proton and neutron. Another six particles known as leptons, marked in green, include one of the most pervasive fundamental particles, the electron, which is responsible for the operation of most household circuits. And finally there are the four gauge bosons highlighted in red, which are of the greatest relevance to the measurement presented in this paper. The gauge bosons are responsible for the mediation of three out of the four fundamental forces in nature: the electromagnetic, strong, and weak interactions [1].

The Higgs boson is an essential component of the Standard Model and plays an important role in the predictive power of the theory. Like much of modern physics, the Standard Model relies heavily on the symmetries of nature. Just as concepts such as conservation of momentum and energy can be tied to the fact that a system is symmetric under translations in space and time[2], much of the mathematical framework of the Standard Model is based on internal symmetries known as gauge symmetries. In

[1] Theorists have yet been unable to incorporate the gravitational force, a pervasive component of the macroscopic world, into the current theory of particle physics.

[2] This result is known as Noether's Theorem and can be attributed to the brilliant German mathematician Emmy Noether.

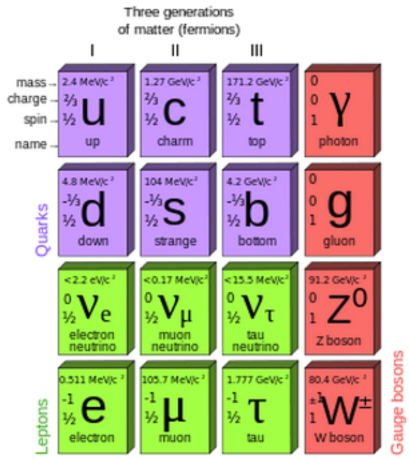

Figure 1: A table summarizing the particles described by the Standard Model of particle physics. The Standard Model encompasses three generations of quarks and leptons as well as four force carrying bosons.

fact there are three gauge symmetries found in the Standard Model[3] each of which predicts a force carrying particle that mediates one of the aforementioned interactions of nature. The photon mediates the electromagnetic interaction. The massless gluon is responsible for the strong interaction, which binds quarks together to form protons and neutrons. And finally, the weak interaction, which causes radioactive decays, is mediated by the massive $W^{\pm}$ and Z bosons. The problem with all of this symmetry is that it predicts that the weak nuclear force is a long range force, something which is not observed in nature. The reason for this discrepancy can be traced back to the fact that the W and Z bosons are not massless particles, but have a mass of roughly 80 and 90 GeV respectively. In addition, these internal gauge symmetries also predict that other fundamental particles, such as the electron, are massless. In order to solve this apparent predicament one needs to introduce a mechanism that keeps the equations that govern the Standard Model's behavior symmetric, but allows for some asymmetric lowest energy states, i.e. 'ground states'. This is accomplished with a theoretical mechanism known as spontaneous symmetry breaking or in this special case the Higgs mechanism.

On July 4th, 2012 the ATLAS and CMS collaborations both announced the discovery of a particle consistent with the Standard Model Higgs boson [1, 2], indicating that the discovery of the mechanism behind spontaneous symmetry breaking in the Standard Model may be at hand. In addition, the ATLAS experiment measured this Higgs-like boson's mass to be close to 125 GeV [3]. This measurement is only the beginning of a challenging program of 'Higgs identification' through which the consistency of

[3] In group theoretic language the symmetries of the Standard Model can be written as $SU(3) \times SU(2) \times U(1)$.

this new boson with the SM Higgs will be verified or disproved. For this reason it is now becoming increasingly important to measure the properties of this new scalar particle as well as its rate of decay for the largest number of experimentally viable decay channels. These analyses could result in tension with the SM Higgs prediction, for instance the rate of one or more measured decay channels may differ from the SM prediction. The simplest mechanism for such a scenario is an enhancement/suppression in loop-induced decays [4] that are naturally sensitive to couplings to new virtual particles, for instance the decay $H \to Z\gamma$ presented in this paper. This would thus be evidence for Beyond the Standard Model (BSM) physics.

The main decay modes being probed in the searches presented on the July 4th announcement are the $H \to \gamma\gamma$ channel, the $H \to WW^* \to 2\ell 2\nu$ channel and the 'golden channel', $H \to ZZ^* \to 4\ell$. However, little attention has been paid to the $H \to Z\gamma \to \ell^+\ell^-\gamma$ channel despite the fact that its event rate is comparable to that of the golden channel for a 125 GeV Standard Model Higgs boson. The main reason for this is the low branching ratio for $Z \to \ell^+\ell^-$, the probability that a Z boson will decay into two leptons, makes the $Z\gamma$ channel statistically limited. Although, the background rate, the number of non-interesting physics processes that contaminate the process of interest, of the $Z\gamma$ channel is higher than that of the $ZZ^* \to 4\ell$ channel there are a few important properties that make a study of the $Z\gamma$ channel compelling: 1) all final state particles can be measured well with the ATLAS detector; 2) the Higgs mass could be measured from the total invariant mass spectrum; 3) the spin of the Higgs can be studied by analyzing the angular distribution of the decay products, and 4) this channel can be used for setting limits on the Higgs coupling constants. In addition, the ratio of $\gamma\gamma$ to $Z\gamma$ branching ratios can be used to discriminate between certain models of new physics [4, 5, 6]. All of these measurements will help to identify this new particle sitting close to 125 GeV as a Standard Model Higgs boson or something more exotic.

This report documents the measurements of the $H \to Z\gamma$ production rate observed using data from pp collisions provided by the LHC. In the following, the theory behind the $H \to Z\gamma$ decay is discussed in Section 2, the ATLAS detector is described in Section 3, and the signal and backgrond simulation samples used in the analysis are presented in Section 4. The event selection criteria are described in Section 5. A comparison between the selected data sample and the simulation is presented in Section 6. The discrimination between signal and background events is performed by means of an unbinned maximum

[4] A loop means that particles of any mass can instantly materialize and then disappear during the decay process. The brief-lived virtual particles are usually W bosons, but other particles with similar behavior can enter the loop, including many beyond the Standard Model particles. This makes decays involving loops very sensitive to new physics at high masses.

likelihood fit, and the estimated signal yield is compared to the one predicted by the Standard Model. The properties of the signal, in terms of the expected yields and the signal model used for the fit are described in Section 7, while the choice of the background model adopted in the fit is motivated in Section 8. After a description of the systematic uncertainties in Section 9, Section 10 presents the results of the combined analysis of the 7 and 8 TeV datasets.

2 Theory

2.1 Production Process

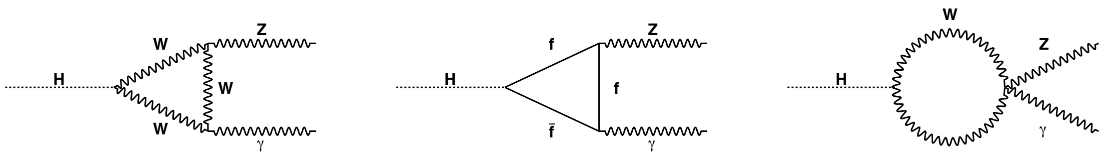

Figure 2: Leading Feynman diagrams for the $H \to Z\gamma$ decay in the Standard Model. Note that in the case of the fermion loop, top quarks dominate.

3 ATLAS Detector

4 Signal and Background Simulation Samples

5 Event Selection

6 Data-driven Background Estimation

7 Signal Properties

8 Background Model

9 Systematic Uncertainties

10 Results

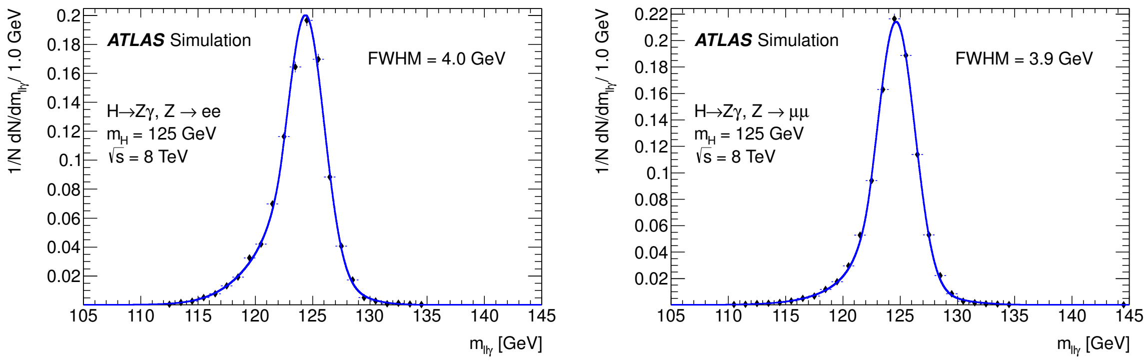

Figure 3: Three-body invariant mass distribution for $gg \to H \to Z\gamma$ selected events in the 8 TeV, $m_H = 125$ GeV signal simulation, after applying all analysis cuts and corrections. The blue solid lines represent the fits to the points of the sum of a Crystal Ball lineshape and a Gaussian function. Left: $Z \to ee$ channel, right: $Z \to \mu\mu$ channel.

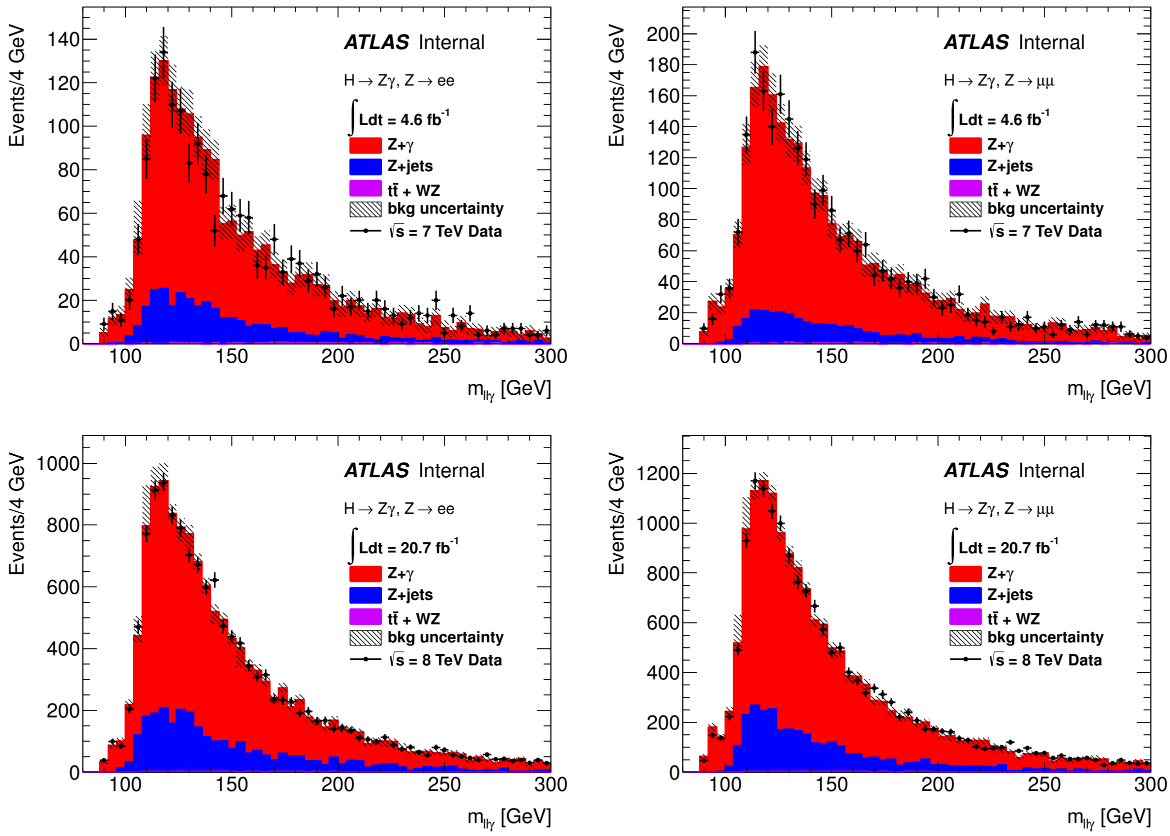

Figure 4: Three-body invariant mass ($m_{\ell\ell\gamma}$) distribution of selected events in data (dots) and from the various background sources (histograms, from the simulation) normalized to the yields determined as described in the text, for $Z \to ee$ (left) and $Z \to \mu\mu$ (right) channels. The small peak near m_Z is from residual FSR Z+γ contamination. The background uncertainty includes statistical uncertainties and systematic uncertainties from the inputs taken from the simulation, as detailed in the text.

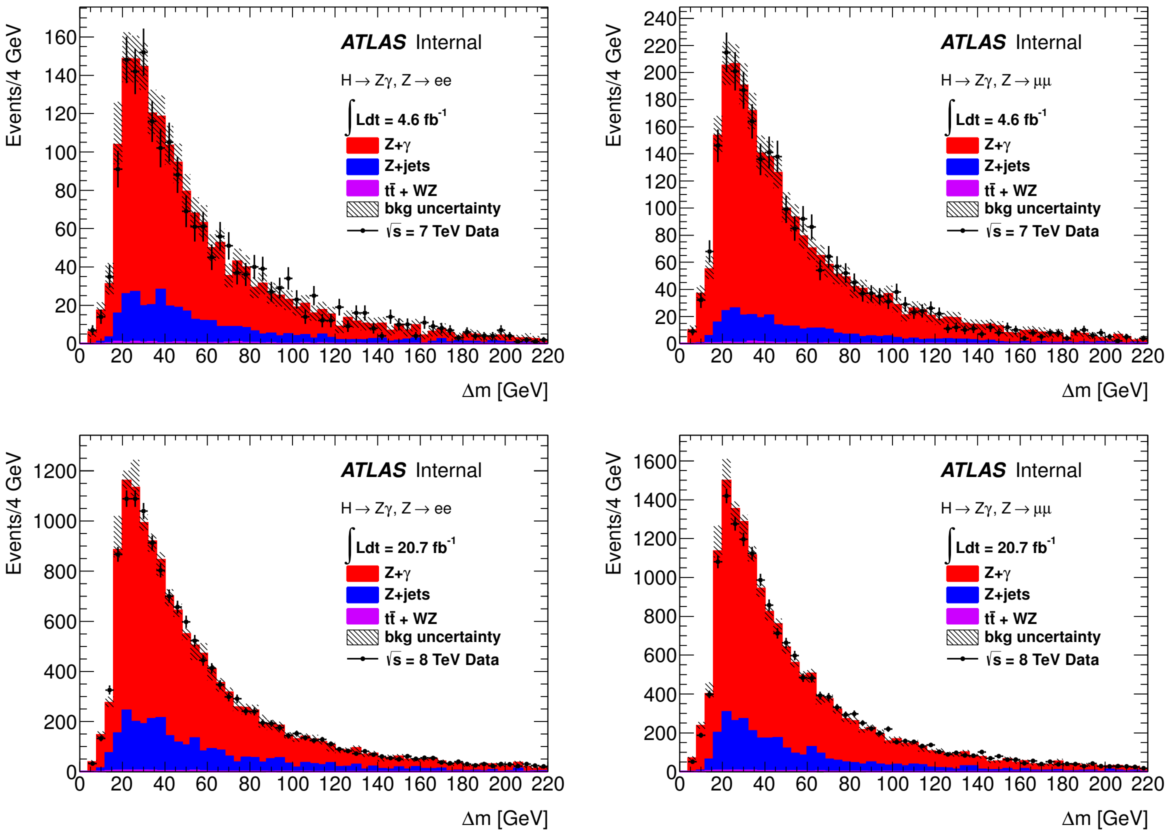

Figure 5: Distribution of the difference Δm between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ for selected events in data (dots) and from the various background sources (histograms) normalized to the yields determined as described in the text, for $Z \to ee$ (left) and $Z \to \mu\mu$ (right) channels. The background uncertainty includes statistical uncertainties and systematic uncertainties from the inputs taken from the simulation.

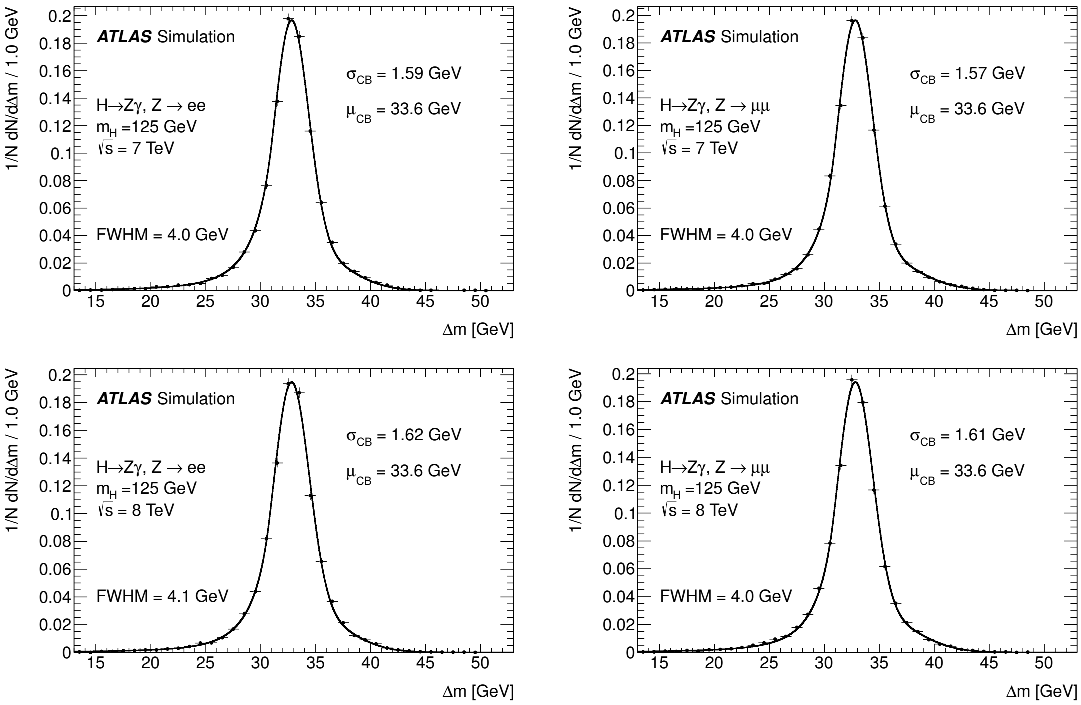

Figure 6: Distribution (normalized to unit area) of the difference Δm between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ for signal events passing the full selection (dots), for $m_H = 125$ GeV and $\sqrt{s} = 7$ (top) or 8 (bottom) TeV. The line overlaid represents the fit of the distribution with a model composed of the sum of a Crystal Ball (CB) and a Gaussian (GA) function. Left: electron channel, right: muon channel.

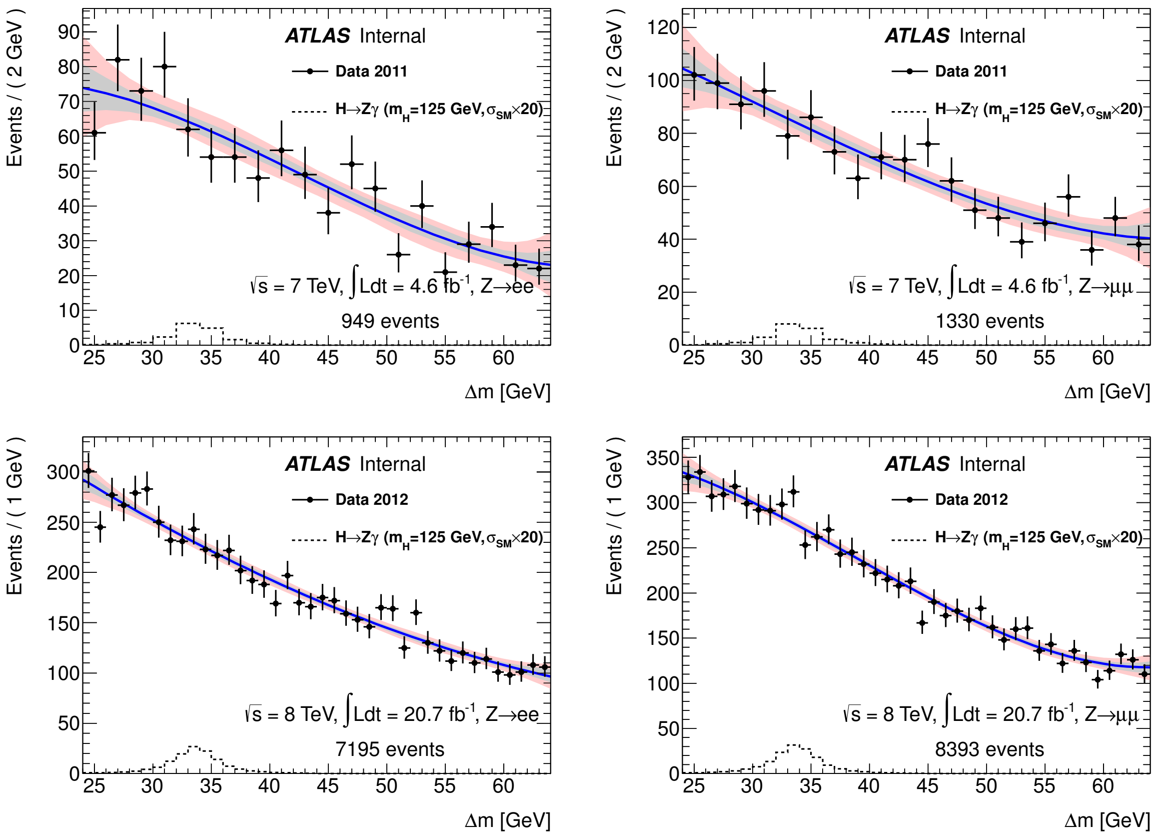

Figure 7: Background-only fits to the distribution of the mass difference Δm of selected events in data, for $Z \to ee$ (left) and $Z \to \mu\mu$ (right), at $\sqrt{s} = 7$ TeV (top) or 8 TeV (bottom). For both 7 and 8 TeV, a third order polynomial is used for the fit. Dots correspond to data, the blue line is the fit result and the gray and light red bands are the 1σ and 2σ uncertainty bands from the statistical uncertainties on the fitted background model parameters. The dashed histograms correspond to the SM signal expectation, for a Higgs boson mass of 125 GeV, scaled by a factor 20 for clarity.

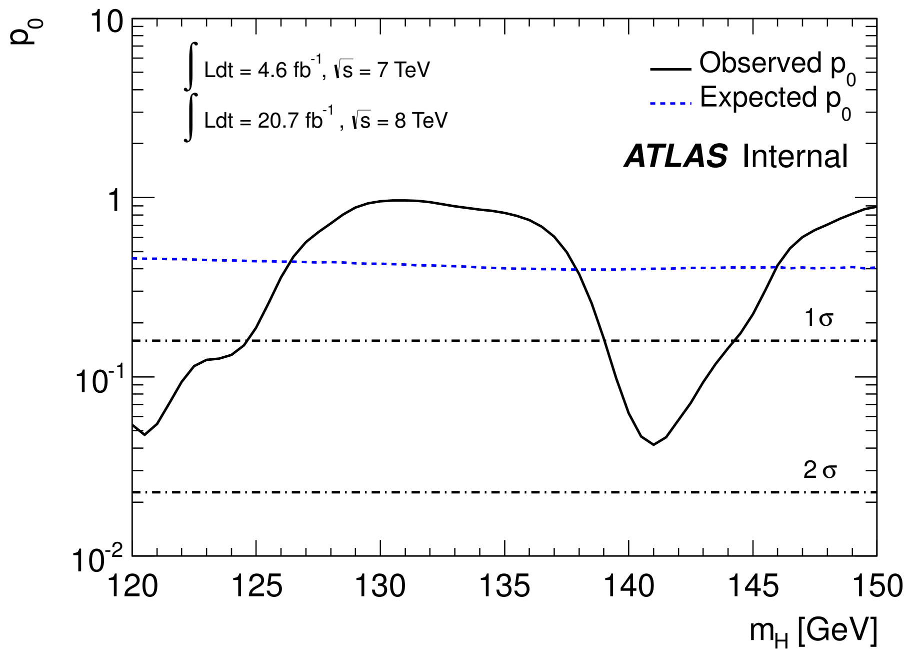

Figure 8: Expected (dashed blue line) and observed (solid black line) p_0 (compatibility of the data with the background-only hypothesis) as a function of the Higgs boson mass, using 4.6 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV and 20.7 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV.

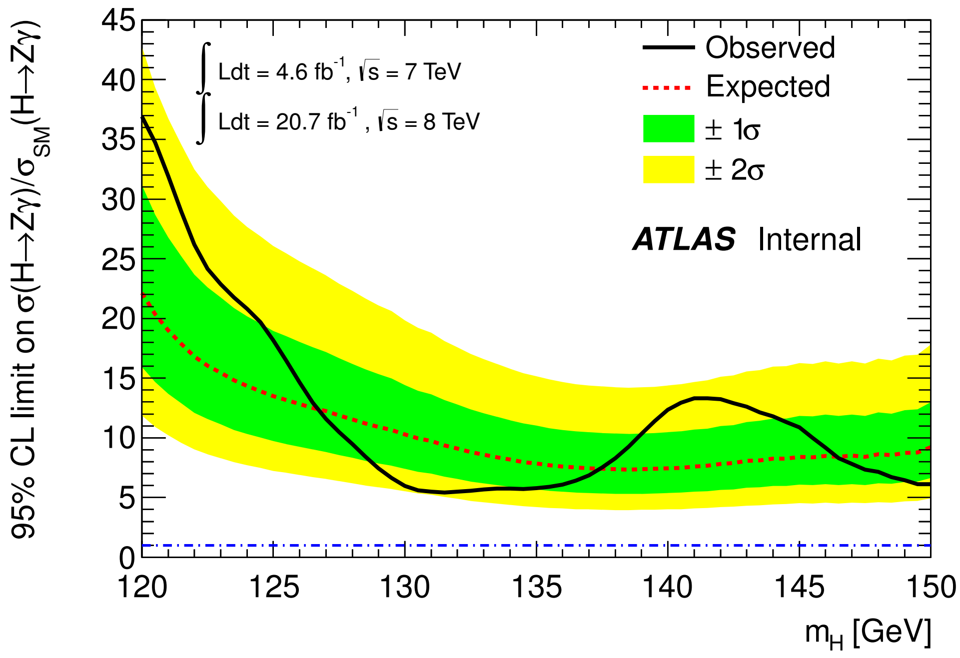

Figure 9: Observed 95% *CL* limits (solid black line) on the production cross section of a SM Higgs boson decaying to $Z\gamma$, as a function of the Higgs boson mass, using 4.6 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV and 20.7 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV. The median expected 95% *CL* exclusion limits (dashed red line) are also shown. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1, arXiv:1207.7214 [hep-ex].

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30, arXiv:1207.7235 [hep-ex].

[3] ATLAS Collaboration, *An update of the combined measurements of the new Higgs-like boson with high mass resolution channels*, ATLAS-CONF-2012-170 (2012) . http://cds.cern.ch/record/1499629.

[4] C.-W. Chiang 1207.1065.

[5] C.-S. Chen 1301.4694.

[6] J. Cao 1301.4641.