

Observation of the Standard Model Higgs boson and search for an
additional scalar in the $\ell^+\ell^-\ell^+\ell^-$ final state with the ATLAS detector

by

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To my family

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Observation of the Standard Model Higgs boson and search for an additional scalar in the $\ell^+\ell^-\ell^+\ell^-$ final state with the ATLAS detector

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Abstract

This thesis presents the observation of a Standard Model Higgs boson (h) and a search for an additional scalar (H) in the $h/H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ channel (four-lepton channel), where ℓ stands for either an electron or a muon. The observation of a Standard Model Higgs boson in the four-lepton channel uses the proton–proton collision data collected with the ATLAS detector during 2011 and 2012 at center-of-mass energies of 7 and 8 TeV. An excess with a local significance of 8.1 standard deviation is observed in the four-lepton invariant mass spectrum around 125 GeV. The mass of the excess measured in $\ell^+\ell^-\ell^+\ell^-$ channel is 125.51 ± 0.52 GeV. Further measurements on the production cross section times branching ratio of the excess agree well with the Standard Model predictions within the experimental uncertainties.

The search for an additional scalar uses an integrated luminosity of 36.1 fb^{-1} proton–proton collision data at a center-of-mass energy of 13 TeV collected with the ATLAS detector during 2015 and 2016. The results of the search are interpreted as upper limits on the production cross section of a spin-0 resonance. The mass range

of the hypothesized additional scalar considered is between 200 GeV and 1.2 TeV. The upper limits for the spin-0 resonance are translated to exclusion contours in the context of Type-I and Type-II two-Higgs-doublet models. This analysis is combined with the same search in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel to enhance the search sensitivities in the high mass region.

Chapter 1

Introduction

The Higgs mechanism [1–5] plays a central role in providing mass to the W and Z vector bosons without violating local gauge invariance. In the Standard Model (SM) of particle physics [6–8], the Higgs mechanism implies a neutral and colorless scalar particle, the Higgs boson. The search for the Higgs boson is the highlight of the Large Hadron Collider (LHC) physics program [9].

Indirect experimental limits on the Higgs boson mass of $m_H < 158$ GeV at 95% confidence level (CL) are obtained from precision measurements of the electroweak parameters that depend logarithmically on the Higgs boson mass through radiative corrections [10]. Direct searches at the Large Electron-Positron Collider (LEP) at CERN placed a lower bound of 114.4 GeV on the Higgs boson mass at 95% CL, using a total of about 2.46 pb^{-1} of e^+e^- collision data at center-of-mass ($\sqrt{s}$) energies between 189 and 209 GeV [11]. The searches for the SM Higgs boson in A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) cover all major Higgs decay channels, including $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow \tau\tau$. This thesis presents the observation of a SM Higgs boson in the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$

decay channel (four-lepton channel) in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector at the LHC.

On July 4th 2012, the ATLAS and CMS collaboration independently announced the observation of a new particle using pp collision data at center-of-mass energies of 7 and 8 TeV produced by the LHC [12, 13]. Three years later, by combining the ATLAS and CMS results, the mass of the discovered particle was precisely measured [14]:

$$125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{sys}) \text{ GeV}$$

Once its mass was determined, other properties of the Higgs boson could be theoretically calculated and experimentally checked. There has been great progress in understanding the main properties of the observed particle: (1) its spin and CP were tested against some other alternative assumptions, which have been excluded at more than 99.9% confidence level using the ATLAS and CMS detectors [15–17]; (2) its CP invariance in the vector boson fusion production were tested in di-tau decay channel and found to be consistent with the SM expectation [18]; (3) its production and decay rates were measured using the combined ATLAS and CMS analyses of the LHC Run 1 pp data. The data were consistent with the SM predictions. [19].

This thesis also presents a search for additional heavy scalar resonances in the four-lepton final state, using similar event selection criteria as used in the SM Higgs boson observation. The search uses 36.1 fb^{-1} of pp collision data collected with the ATLAS detector during 2015 and 2016 at a center-of-mass energy of 13 TeV. The search looks for a peak structure on top of the SM background in the four-lepton invariant mass spectrum. With a good mass resolution and relatively low background, the $\ell^+\ell^-\ell^+\ell^-$ final state is suited to search for narrow resonances in the mass range

200 – 1000 GeV. Final results are interpreted as upper limits on the cross section times branching ratio for different signal hypotheses. The first hypothesized signal is a heavy scalar particle under the narrow width approximation (NWA), whose natural width is set to 4 MeV in the Monte Carlo generation. The heavy scalar is assumed to be predominately produced by the gluon-fusion and vector boson fusion processes. As various models also favor a large width resonance, three benchmark models with a width of 1%, 5% and 10% of the resonance mass are studied. For large-width hypotheses, the interference between the additional heavy scalar and the SM Higgs boson as well as the additional heavy scalar and the $gg \rightarrow ZZ$ continuum background are taken into account. The results for a NWA signal are combined with those in the $\ell^+\ell^-\nu\bar{\nu}$ final state to enhance the search sensitivity over the full mass range. The results presented in this thesis extend previous searches for an additional heavy scalar using 7 and 8 TeV pp collision data published by ATLAS [20]. Similar results were also reported by CMS [21].

This thesis is organized as the following: Chapter 2 introduces an overview of the Standard Model and beyond, providing physics motivations for the two analyses. The LHC and ATLAS detector are described briefly in Chapter 3. Collision data and simulated Monte Carlo data are summarized in Chapter 4, followed by the reconstruction of physics objects in ATLAS in Chapter 5. The common aspects in the two analyses including event triggers, the selection criteria of four-lepton candidates, the methods of background estimation and the statistical treatment, are summarized in Chapter 6. The observation of a SM Higgs boson in the $\ell^+\ell^-\ell^+\ell^-$ final state is presented in Chapter 7 and the search for additional heavy scalars in the $\ell^+\ell^-\ell^+\ell^-$ final state along with the combination with the results from $\ell^+\ell^-\nu\bar{\nu}$ final state are

presented in Chapter 8. Finally, Chapter 9 gives the conclusion and outlook.

Chapter 2

The Standard Model and Beyond

2.1 Introduction to the Standard Model

The Standard Model (SM) [6–8] of particle physics describes the interactions of elementary particles through the strong, weak, and electromagnetic forces. Elementary particles of half-integer spin are called *fermions*. Fermions with spin- $\frac{1}{2}$ constitute the visible matter in the universe. These fermions include the charged *leptons* (e , μ , τ), their corresponding neutral *neutrinos* (ν_e , ν_μ , ν_τ), the *quarks* (u , d , c , s , t , b), and the antiparticles of each of the leptons and quarks. Elementary particles with integer spin are called *bosons*. Bosons that are mediators of the interactions between elementary particles are called *gauge* bosons. The γ , $W^\pm$ and Z bosons are mediators for the electroweak interactions, and the gluons g are mediators for the strong interactions. All these known gauge bosons have a spin of 1, therefore they are vector bosons. In addition, the Higgs boson, which is responsible for the mass of the W and Z bosons, has a spin of 0. A summary of the SM particles is provided in Figure 2.1.

The Standard Model is a renormalizable [22], locally invariant gauge theory [23]

Standard Model of Elementary Particles

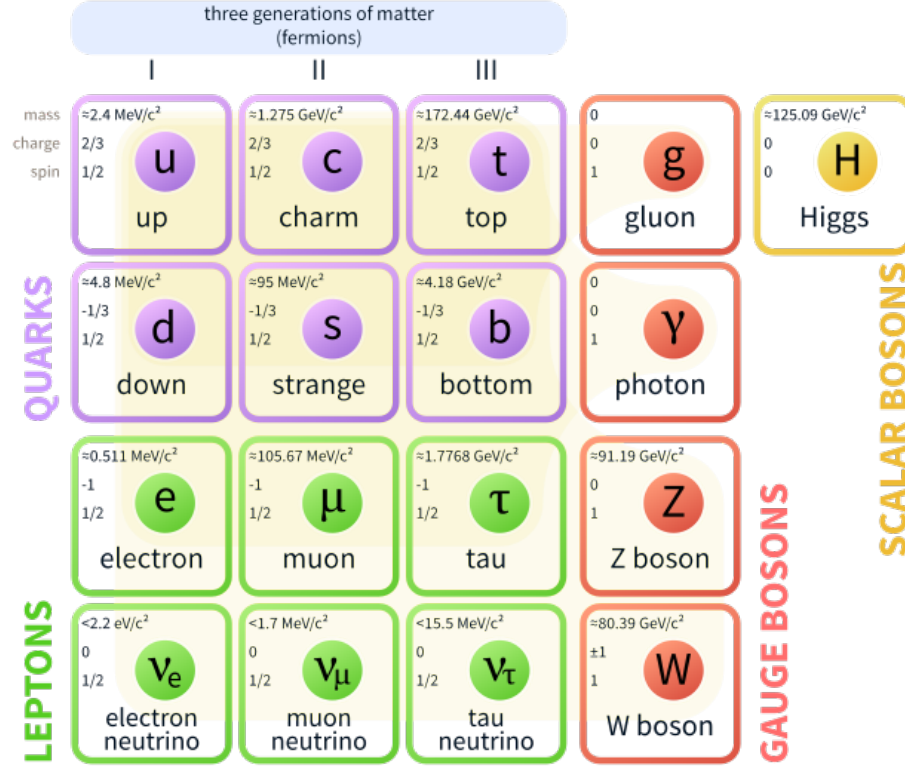


Figure 2.1: Elementary particles in the Standard Model, including quarks, leptons, gauge bosons and the Higgs boson. Their masses, charges and spins are also presented. Picture is taken from www.wikipedia.com.

based on an $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ symmetry group. The $SU(3)_C$ symmetry group describes the *color* symmetry of the strong interaction. The eight generators of $SU(3)_C$ symmetry group correspond to eight color quantum states of the massless gluon. Quantum chromodynamics (QCD) describes the strong interactions, and was developed during the 1960s based on the $SU(3)_C$ symmetry group [24, 25]. During that time, the electromagnetic and weak interactions were unified into a local gauge theory of electroweak interactions based on the $SU(2)_L \otimes U(1)_Y$ symmetry group,

the Glashow-Weinberg-Salam (GWS) electroweak theory [6–8]. The $SU(2)_L$ symmetry group describes the *isospin* (I) symmetry of the electroweak interaction with three generators (A_μ^a). The $U(1)_Y$ symmetry group, describing the *hypercharge* Y ($Y = Q - I_3$, where Q is the electric charge) symmetry of the electroweak interactions, corresponds to a unitary transformation on a complex 1-dimension vector, with one generator (B_μ). The four generators of the $SU(2)_L \otimes U(1)_Y$ symmetry group correspond to the four gauge bosons. The origin of the masses of these $W^\pm$ and Z bosons is explained by a mechanism that spontaneously breaks a local gauge symmetry.

2.2 The Higgs mechanism

The problem of giving masses to elementary particles was solved in 1964, first in a paper by Englert and Brout [1] and later in a series of papers by Higgs [2, 3], and others [4, 26]. These papers demonstrated that spontaneous symmetry breaking of a local gauge symmetry is gauge invariant: the Higgs mechanism.

Weinberg applied this Higgs mechanism to the leptons [7]. He proposed a scalar doublet $\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ which is a self-interacting $SU(2)_L$ complex doublet (four real degrees of freedom) with hypercharge $Y = \frac{1}{2}$ and isospin $I = \frac{1}{2}$:

$$V(\phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (2.1)$$

The λ term describes quartic self-interactions of the scalar fields. When $m^2 < 0$ and $\lambda > 0$, the neutral component of the scalar doublet ϕ^0 acquires a non-zero vacuum expectation value (VEV) ν , inducing the spontaneous breaking of the SM local gauge symmetry. The symmetry is still present in the theory; only the vacuum state breaks

the symmetry. Consequently the $W^\pm$ and Z bosons acquire masses,

$$m_{W^\pm}^2 = \frac{g^2 \nu^2}{4}, \quad m_Z^2 = \frac{(g'^2 + g^2) \nu^2}{4},$$

where g and g' are the $SU(2)_L$ and $U(1)_Y$ gauge couplings. The fermions of the SM can also acquire masses through their Yukawa interactions with the scalar field. The discovery of the $W^\pm$ [27, 28] and Z bosons [29, 30] in 1983 using the Super Proton Synchrotron at CERN provided a strong experimental support on the gauge theory of the electroweak interactions.

In the Higgs mechanism, of the initial four degrees of freedom of the scalar field, two are absorbed by the $W^\pm$ gauge bosons, and one by the Z gauge boson. The one remaining degree of freedom, H , is the physical Higgs boson — a new scalar particle. Its mass is given by $m_H = \sqrt{2\lambda} \nu$, where λ is the Higgs self-coupling parameter in Equation 2.1 and ν is the VEV, about 246 GeV. The quartic coupling λ is a free parameter in the SM, hence the Higgs mass is not determined. Therefore a direct search for the SM Higgs boson becomes very challenging, requiring detailed studies of the Higgs boson properties for a large mass range.

2.3 Higgs boson production and decay mechanisms at the LHC

The SM Higgs boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Ref. [31–34].

Higgs boson production mechanisms In the SM, Higgs boson production at the LHC mainly occurs through the following processes, listed in order of decreasing cross section at the Run 1 center-of-mass energies:

- gluon fusion production $gg \rightarrow H$, namely ggF (Fig. 2.2(a));
- vector boson fusion production $qq \rightarrow qqH$, namely VBF (Fig. 2.2(b));
- associated production with a W boson, $qq \rightarrow WH$, namely WH (Fig. 2.3(a)), or with a Z boson, $pp \rightarrow ZH$, namely ZH , including a small ($\sim 8\%$) from $gg \rightarrow ZH$ ($ggZH$) (Figs. 2.3, 2.3(b), 2.3(c)); WH and ZH are collectively named as VH .
- associated production with a pair of top (bottom) quarks, $qq, gg \rightarrow t\bar{t}H(b\bar{b}H)$, namely $t\bar{t}H$ or $(b\bar{b}H)$ (Fig. 2.4).

Table 2.1 provides the cross section of a Higgs boson with $m_H = 125$ GeV for different production processes at $\sqrt{s} = 7$ and 8 TeV.

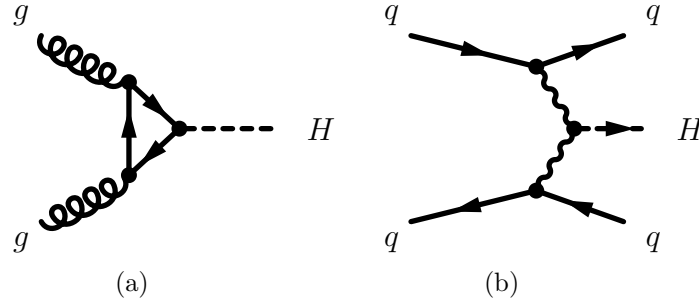


Figure 2.2: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) ggF and (b) VBF production processes.

For a SM Higgs boson of mass around 125 GeV, the largest contribution of its total production cross section comes from the ggF process, because of the abundance of gluons in the protons. The massless gluons would not interact with the Higgs boson except through quantum loops of massive quarks, such as top or bottom quarks. Because of the top/bottom quark interference in the loops, the ggF production process provides sensitivity, although limited, to the relative signs of the Higgs coupling to

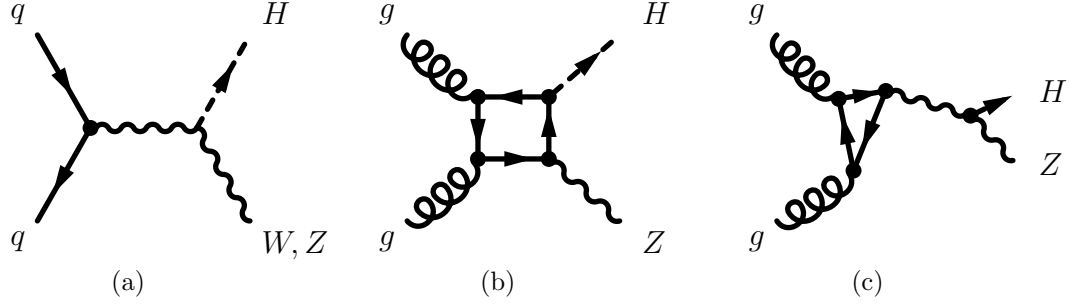


Figure 2.3: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) $qq \rightarrow VH$ and (b, c) $gg \rightarrow ZH$ production processes.

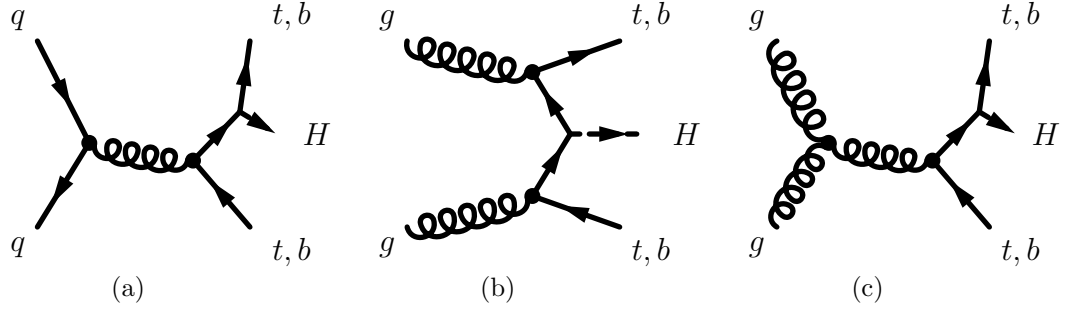


Figure 2.4: Examples of leading-order Feynman diagrams for Higgs production via the $qq/gg \rightarrow ttH$ and $qq/gg \rightarrow bbH$ processes.

top and bottom quarks [19]. The ggF production cross section is calculated at up to next-to-next-to-leading order (NNLO) in QCD corrections [35–41]. Next-to-leading order (NLO) in electroweak (EW) corrections are applied [42, 43], as well as the QCD soft-gluon re-summations at next-to-next-to-leading logarithmic (NNLL) [44]. These calculations, which are described in Refs [45–48], assume a factorization between the QCD and EW corrections. The transverse momentum spectrum of the Higgs boson in the ggF process follows the HqT calculation [49], which includes QCD corrections at NLO and QCD soft-gluon re-summations up to NNLL; the effects of finite quark masses are also taken into account [50].

The second-largest contribution is from the VBF production process, of which

Table 2.1: The Standard Model predictions for the Higgs boson production cross section together with their theoretical uncertainties. The value of the Higgs boson mass is assumed to be $m_H = 125$ GeV. The uncertainties in the cross sections are evaluated as the sum in quadrature of the uncertainties resulting from variations of the QCD scales, parton distribution functions, and α_s .

production process	Cross section [pb]	
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ggF	15.1 ± 1.6	19.3 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.58 ± 0.02	0.70 ± 0.02
ZH	0.34 ± 0.01	0.42 ± 0.02
$t\bar{t}H$ and $b\bar{b}H$	0.24 ± 0.04	0.33 ± 0.05
Total	17.5 ± 1.7	22.3 ± 2.1

cross section is calculated at full QCD and EW corrections up to NLO [51–54] and approximate NNLO QCD corrections [55]. In the VBF production, the Higgs boson is produced with two forward, separated and energetic jets, which are usually used in the experiment to distinguish the events of VBF production process from those of other production processes.

The next important Higgs production is the VH process, where V stands for a $W^\pm$ or a Z boson. Their cross sections are calculated up to NNLO in QCD corrections [56–58] and NLO in EW corrections [59], except for the $gg \rightarrow ZH$ production process, calculated only at NLO in QCD with a theoretical uncertainty assumed to be 30%. The unique decay products from the associated vector boson are experimentally used to discriminate the events from the VH processes against those of other production processes, or to trigger the Higgs events in some analyses, such as the search for Higgs boson in the $b\bar{b}$ decay channel.

The $t\bar{t}H$ production process bears a relatively low cross section, but contains significant physics information because it provides a direct measurement of the top-Higgs Yukawa coupling. Its cross section is estimated up to NLO QCD [60–64]. The associated top quark pair further decays to other products, resulting in a complicated multi-object final state where the correlations of all the decay products are of great importance. Thus, multivariate techniques are widely used in the search for $t\bar{t}H$ production process [65, 66].

Higgs boson decay mechanisms The Higgs boson couplings to the fundamental particles are directly related to their masses. More precisely, the SM Higgs couplings to fermions are linearly proportional to the fermion masses, whereas the couplings to vector bosons are proportional to the square of the boson masses. As a result, the dominant Higgs boson decay mechanisms involve the coupling of Higgs boson to W , Z bosons and/or the third or second generation quarks and leptons, depending on the kinematic accessibility. Figure 2.5(a) shows the branching ratio of each decay mode for different Higgs boson masses. For a light Higgs boson the dominant decay mode is the $b\bar{b}$ final state as the WW , ZZ and $t\bar{t}$ decay modes are kinematically suppressed.

The branching ratios and the relative uncertainty for a SM Higgs boson with $m_H = 125$ GeV is shown in Table 2.2. Although the branching ratio of $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ is very small for a low mass Higgs boson, this decay channel possesses an excellent mass resolution (1–2% for $m_H = 125$ GeV), and a good signal to background ratio (about 2 for $m_H = 125$ GeV); thus, it is suitable for the search for a resonance in the range of 200 and 1000 GeV.

The intrinsic width of a Higgs boson (Γ_h) predicted by the SM increases dramati-

Table 2.2: The branching ratios and the relative uncertainty for a SM Higgs boson with $m_H = 125$ GeV.

Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow \gamma\gamma$	2.27×10^{-3}	+5.0%
$H \rightarrow ZZ$	2.62×10^{-2}	-4.9%
$H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ (ℓ is e or μ)	1.40×10^{-4}	+4.3%
$H \rightarrow W^+W^-$	2.14×10^{-1}	-4.1%
$H \rightarrow \tau^+\tau^-$	6.27×10^{-2}	+4.3%
$H \rightarrow b\bar{b}$	5.84×10^{-1}	-4.1%
$H \rightarrow Z\gamma$	1.53×10^{-3}	+4.3%
$H \rightarrow \mu^+\mu^-$	2.18×10^{-4}	-4.2%
		+5.7%
		-5.7%
		+3.2%
		-3.3%
		+9.0%
		-8.9%
		+6.0%
		-5.9%

ically when its mass increases, as shown in Figure 2.5(b). At a mass of 1 TeV, its width is about 600 GeV, which is too large to form a proper resonance. In the search for additional heavy scalars, the intrinsic width of a heavy scalar is customarily assumed to be negligibly small comparing to detector resolution, dubbed as the narrow width approximation (NWA); or it is set to a benchmark width, such as 1%, 5% or 10% of its mass.

2.4 Two Higgs Doublet Model

The two Higgs doublet model is motivated as shown in Ref. [67]. The best known one is from the supersymmetry [68] (SUSY). Supersymmetric theories require at least two scalar fields in order to give masses simultaneously to the charge $\frac{2}{3}$ and charge $\frac{-1}{3}$ quarks (i.e. up-like and down-like quarks). The two Higgs doublet model assumes there are two Higgs fields (Φ_1 and Φ_2), each with four degrees of freedom, hypercharge $Y = \frac{1}{2}$ and isospin $I = \frac{1}{2}$; consequently the potential energy term of

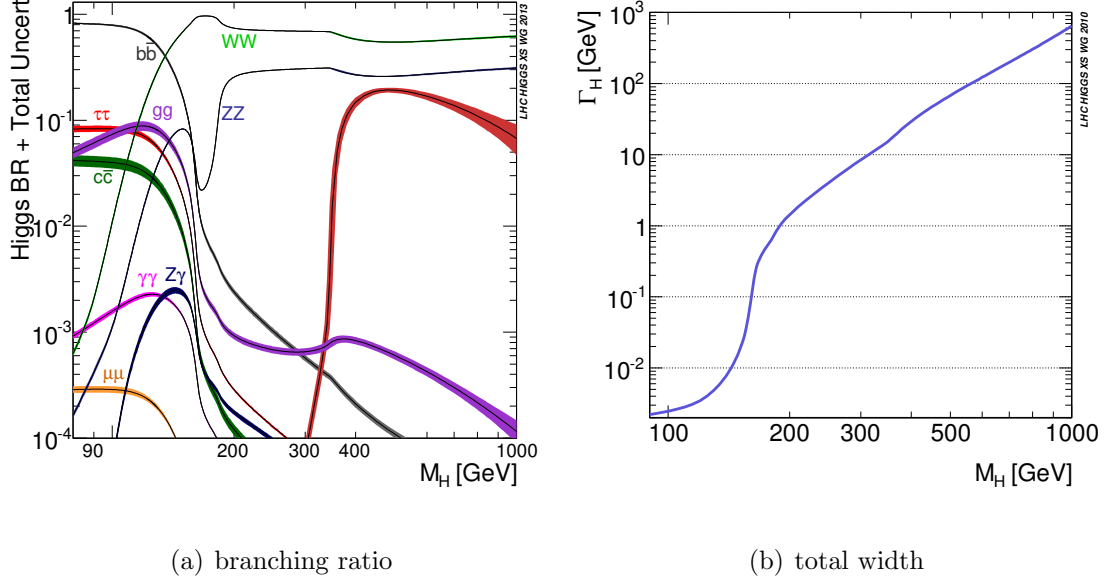


Figure 2.5: (a) shows the branching ratio of different Higgs decay modes for different Higgs boson masses. The theoretical uncertainties are shown as bands. (b) shows the total width of a SM Higgs boson as a function of the Higgs mass hypothesis.

Equation 2.1 becomes:

$$\begin{aligned}
 V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\
 & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 \\
 & + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]
 \end{aligned} \tag{2.2}$$

where all the parameters are real. The minimization of this potential results in two vacuum expectation values (VEVs): ν_1 and ν_2 . As described in the Higgs mechanism, the non-zero VEVs spontaneously break the electroweak gauge symmetry. In total there are eight degrees of freedom in the two scalar fields, of which three are absorbed by the $W^\pm$ and Z boson just as in the Standard Model. There are five remaining degrees of freedom — five Higgs bosons: two CP-even Higgs bosons, denoted as H and h , where h could be the discovered Higgs boson at 125 GeV and the H is assumed

to be heavier than the h ; two charged Higgs bosons ($H^\pm$) and one CP-odd Higgs boson (A). There are eight independent parameters of interest:

- (a) the mass of the Higgs bosons: m_H , m_h , m_A , and $m_{H^\pm}$.
- (b) the mixing angle between the two CP-even Higgs bosons, α .
- (c) the ratio of the vacuum expectation value of the two doublets, $\tan \beta = \nu_1/\nu_2$.
- (d) the m_{12} parameter of the potential.

m_h is set to 125 GeV to agree with the observed Higgs boson. It is assumed that other Higgs bosons (m_A , $m_{H^\pm}$) are heavy enough so that the heavy CP-even Higgs boson, H , does not decay to them. The cross sections and branching ratios are calculated at next-to-next-to-leading order with the SusHi and 2HDMC programs [39, 42, 69–73].

The two Higgs doublets Φ_1 and Φ_2 can couple to leptons and up- and down-type quarks in four different types [67]. Since the ZZ final state has no sensitivity to the coupling of the Higgs boson to leptons, only Type-I and Type-II models are discussed. In the Type-I model, Φ_2 couples to all quarks and leptons, while Φ_1 does not couple to SM particles. In the Type-II model, Φ_2 couples to only up-type quarks, while Φ_1 couples to down-type quarks and leptons. In Type-I and Type-II models, the coupling of the heavy CP-even Higgs boson H to vector bosons is proportional to $\cos(\beta - \alpha)$. In the limit of $\cos(\beta - \alpha) \rightarrow 0$ the lighter CP-even Higgs boson h becomes indistinguishable from the observed SM Higgs boson.

Chapter 3

The LHC and ATLAS detector

3.1 The LHC

The Large Hadron Collider (LHC) at the European Organization for Nuclear Physics (CERN) is the world's largest and most powerful particle accelerator. It consists of a particle accelerator located in a 27 kilometers long circular channel, 100 meters beneath the France-Switzerland border near Geneva, Switzerland. LHC's first research run took place from 30 March 2010 to 13 February 2013 at an initial energy of 3.5 TeV per beam (equally, center-of-mass-energy $\sqrt{s} = 7$ TeV), which was raised to 4 TeV per beam ($\sqrt{s} = 8$ TeV) in 2012 and stayed at 6.5 TeV per beam ($\sqrt{s} = 13$ TeV) in 2015 and 2016. The proton-proton (pp) collisions produced by the LHC at center-of-mass-energies of 7 and 8 TeV during 2011 and 2012 are collectively named as the LHC Run 1 data set, and those at $\sqrt{s} = 13$ TeV during 2015 and 2016 are named as the LHC Run 2 data set in this thesis.

Hadronic cross section Scattering process at the LHC can be classified as either hard or soft. Quantum Chromodynamics (QCD) is the underlying theory for all such processes, but the approach and level of understanding is very different for the two cases. For hard processes, such as Higgs production, its partonic cross section ($\hat{\sigma}$) can be predicted with good precision using perturbation theory. For soft processes, such as underlying events, the rates and event properties are dominated by non-perturbative QCD effects, which are less well understood. Using the QCD factorization theorem [74], the hadronic cross section for a general gluon-initiated production of a particle X ($pp \rightarrow X$) at LHC, as an example, can be formulated as:

$$\sigma_{pp \rightarrow X} = \int dx_1 f_{g/p}(x_1, \mu_F^2) \int dx_2 f_{g/p}(x_2, \mu_F^2) \hat{\sigma}(x_1 p_1, x_2 p_2, \mu_R^2, \mu_F^2)$$

where x_1 and x_2 is the fractional momentum of gluon over the incoming protons; p_1 and p_2 are the momentum of incoming protons; μ_F is the factorization scale, which is the scale that separates hard and soft processes, and μ_R is the renormalization scale for the QCD running coupling α_s ; μ_F and μ_R , collectively named as QCD scales, are usually set to a common value; $f_{g/p}$ is the parton distribution function of gluon with a momentum fraction of x measured in the momentum transfer of μ_F . The parton distribution functions, encoding information about the proton's deep structure, are obtained from fitting deep inelastic scattering structure function data and then evolved with the DGLAP equations [75] as a function of energy scales to meet the needs of higher energy at the LHC. The parton cross section $\hat{\sigma}$ of a hard process can be calculated with perturbative QCD (pQCD) at different orders of α_s , thanks to the asymptotic freedom of the QCD [76]. However, other than in simplest cases, the hadronic cross sections are calculated automatically with programs such as MadGraph [77].

Luminosity The luminosity $\mathcal{L}$ of a pp collider can be expressed as

$$\mathcal{L} = R_{\text{inel}}/\sigma_{\text{inel}} \quad (3.1)$$

where R_{inel} is the rate of inelastic collisions and σ_{inel} is the pp inelastic cross-section. For a storage ring, operating at a revolution frequency f_r and with n_b bunch pairs colliding per revolution, this expression can be rewritten as

$$\mathcal{L} = (\mu n_b f_r)/\sigma_{\text{inel}} \quad (3.2)$$

where μ is the average number of inelastic interactions per bunch crossing. The definition in Equation 3.1 and 3.2 is also referred to as *instantaneous luminosity* and is usually expressed in units $\text{cm}^{-2}\text{s}^{-1}$. As running conditions vary with time, the luminosity of a collider also has a time dependence. The integral over time is called *integrated luminosity*, which is commonly denoted with $L = \int \mathcal{L} dt$, and measured in units b^{-1} . One further distinguishes *delivered integrated luminosity*, which refers to the integrated luminosity which the LHC has delivered to an experiment, and *recorded integrated luminosity*, which refers to the amount of data that has actually been stored to disk by the experiment. The delivered luminosity can be written in terms of the LHC parameters as:

$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \quad (3.3)$$

where n_1 and n_2 are the number of protons per bunch in beam 1 and beam 2 respectively, and Σ_x and Σ_y characterize the horizontal and vertical convolved beam widths, which could be directly measured using dedicated beam-separation scans, also known as van der Meer (*vdM*) scans [78, 79]. Details of the determination of the luminosity in pp collision using the ATLAS detector at the LHC can be found at Ref [80–82].

Some parameters The LHC is designed to collider two proton beams head-by-head, each of the two beams consisting of 2800 bunches of protons per revolution and each bunch containing about 1.25×10^{11} protons, with the revolution frequency of the beam f_r about 11.2 kHz. Furthermore the inelastic cross section is about 80 micro-barn (mb) at 8 TeV, and about 100 mb at 13 TeV¹. And the average number of inelastic interactions per bunch crossing reported by ATLAS for the LHC Run 1 and Run 2 data sets are shown in Figure 3.1.

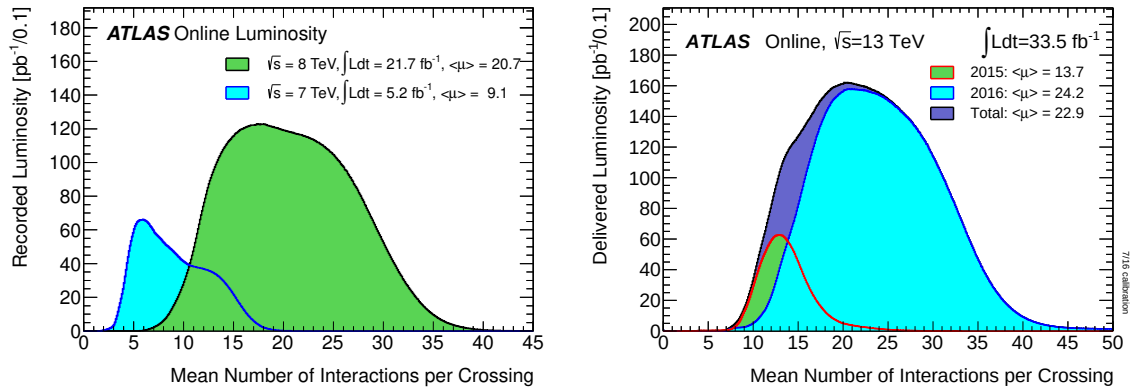


Figure 3.1: The luminosity-weighted distribution of the mean number of interactions per bunch crossing for the 2011 and 2012 pp collision data (left), and 2015 and 2016 pp collision data (right).

Pileup Due to the high instantaneous luminosity, as well as the small separation between collisions, multiple interactions can happen in one single event. Figure 3.1 shows the luminosity-weighted distribution of the mean number of interactions per bunch crossing for LHC Run 1 and Run 2 data. This effect is collectively called pileup, and is generated in two forms: (1) **In-time pileup**: Multiple pp collisions

¹1mb = 10^{-3} b, 1 b = 10^{-24} cm².

in the same bunching crossing. Usually collisions associated with the most energetic physics objects are of physics interest, while others add additional soft energy that must be corrected for. This type of pileup directly relates to the average number of interactions per bunch crossing, μ . The larger the μ is, the stronger the in-time pileup is. (2) **Out-of-time pileup**: Electronic signals from previous bunch crossing still present in the detector, causing this effect. For example, the LAr calorimeters signal length is approximately 500 ns, compared to the bunch spacing of 50 ns in Run 1 data set. Lots of efforts are dedicated to mitigate the pileup effects in the particle reconstruction and identification.

3.2 The ATLAS detector

A Toroidal LHC Apparatus (ATLAS) is a multi-purpose detector with a forward-backward symmetric cylindrical geometry and a solid angle ² coverage of nearly 4π . A detailed description of the ATLAS detector can be found in Ref. [83]. Figure 3.2 shows the overall view of the ATLAS detector. Its dimensions are 25 m in height and 44 m in length. The overall weight is approximately 7000 tonnes. The ATLAS detector consists of three sub-detectors: inner detector, calorimeter and muon spectrometer.

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Distance between two particles are quantified by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where $\Delta\eta$ is the difference of the two particles in η , and $\Delta\phi$ is the difference in ϕ .

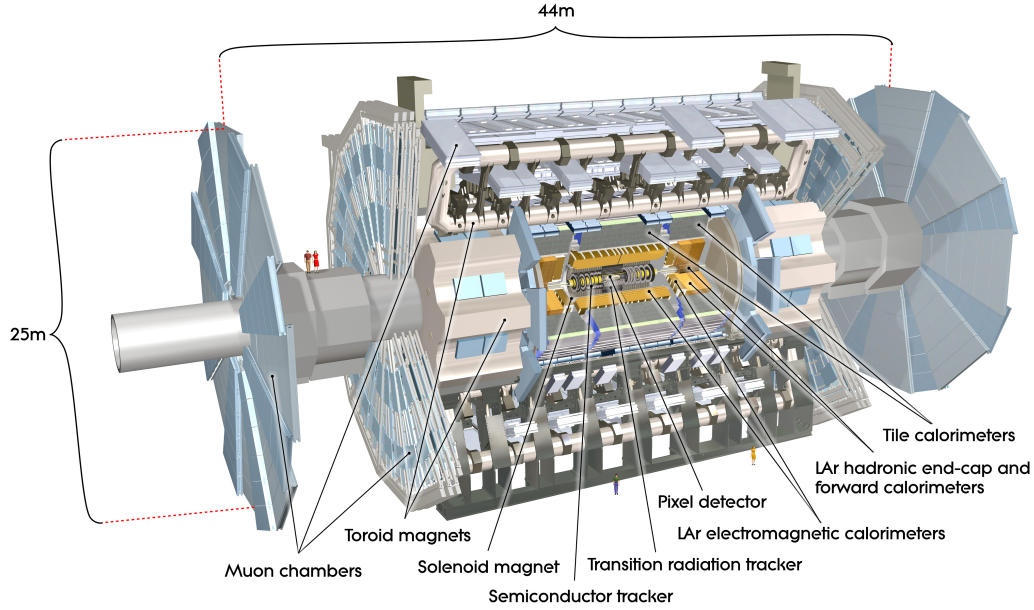


Figure 3.2: Cut-away view of the ATLAS detector. Its dimensions are 25 m in height and 44 m in length. The overall weight is approximately 7000 tonnes.

3.2.1 Inner detector

The inner detector, shown in Figure 3.3, immersed in a 2 T magnetic field, provides precision measurements of the tracks left by electrically charged particles traversing through the magnetic field. It has complete azimuthal coverage in the range $|\eta| < 2.5$. It is composed by a pixel detector, a silicon strip detectors (SCT) and a transition radiation trackers (TRT). The pixel detector measures the x, y, z coordinates of the passed charged particle; the SCT, with pairs of single-sided sensors glued back-to-back, provides 8 hits per track; and the TRT provides 35 hits per track on-average in the range $|\eta| < 2.0$. The innermost pixel layer, usually dubbed as B-layer, is of particular importance in finding hadronized bottom quarks and in rejecting converted photons from real electrons. After the long shutdown during 2014, a Insertable B-layer

(IBL) [84] was added between beam pipe and the original B-layer as a fourth layer to the pixel detector at a mean radius of 3.2 cm. The IBL offers better track and vertex reconstruction performance at the higher luminosity in Run 2 and mitigates the impact of radiation damage to the original innermost layer. It also improves the resolution of primary vertex finding ³ by 28% and the uncertainty on the impact parameter by 25%. Consequently, the rejection of light jets in the $t\bar{t}$ events for a B-hadron efficiency of 60% is increased by 1.9. The overall tracking performances can be found in Ref. [85]. In general the inner detector provides precision measurements of the momentum of charged particles with a decent resolution: $\sigma/p_T = 0.05\% p_T \oplus 1\%$, where p_T is the particle's momentum in the unit GeV.

3.2.2 Calorimeters

Outside of the inner detector are the electromagnetic and hadronic calorimeters, which have complete azimuthal coverage in the range $|\eta| < 4.9$. In the central barrel, a high-granularity liquid-argon (LAr) electromagnetic sampling calorimeter with lead absorbers is surrounded by a hadronic sampling calorimeter (Tile) with steel absorbers and active scintillator tiles. The LAr technology is also used in the calorimeters in endcap, with fine granularity and lead absorbers for EM showers, and with reduced granularity and copper absorbers for hadronic showers. Solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules (FCal) that are optimized for electromagnetic and hadronic measurements respectively. Figure 3.4 shows a cut-view of these calorimeters. To achieve a high spatial resolution, the calorimeter cells are arranged in a projective geometry with fine segmentation

³The primary vertex is defined as the vertex with the highest sum of p_T of tracks associated to it

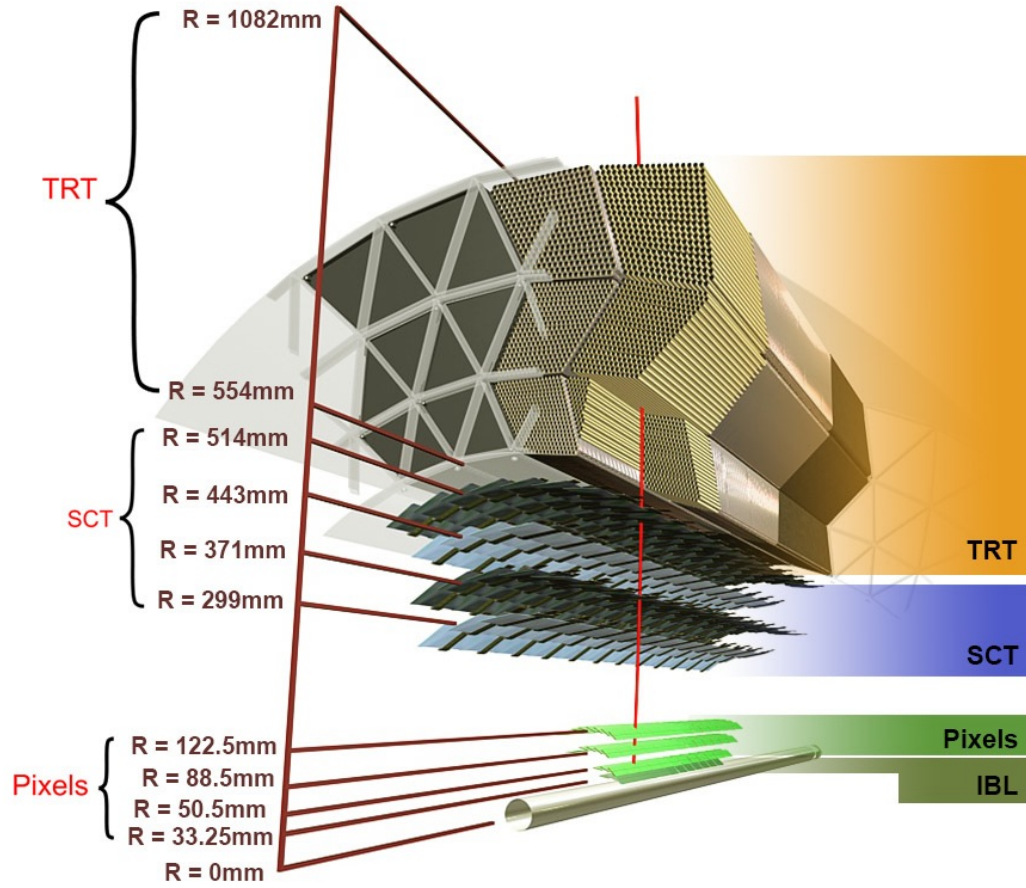


Figure 3.3: Drawing shows the sensors and structural elements traversed by a charged track of 10 GeV in the barrel inner detector (the red line).

in ϕ and η . Each calorimeters is then longitudinally segmented into multiple layers, capturing the shower development in depth. In both EM and Tile calorimeters, most of the absorbers are in the second layer, while in the hadronic endcap, absorbers are more evenly spread between layers. In the region $|\eta| < 1.8$, a pre-sampler detector is used to correct for the energy lost of electrons and photons due to upstream materials of the calorimeter.

Radiation length, which is the mean distance over which a high-energy electron

loses all but $1/e$ of its energy, and $\frac{7}{9}$ of the mean free path for pair production by a high-energy photon, is an appropriate scale length for describing the size of EM calorimeter. The EM calorimeter is over 22 radiation lengths in depth, ensuring that there is little leakage of EM showers into the hadronic calorimeter. Similarly, interaction length, which is the mean path length required to reduce the numbers of relativistic charged particles by the factor $1/e$, is used to describe the size of hadronic calorimeters. The total depth of hadronic calorimeters is over 9 interaction lengths in the barrel and over 10 interaction lengths in the endcap, achieving a good containment of hadronic shower. When a hadronic shower is not completely contained, signals in the muon spectrum are then used to correct the energy of the hadronic shower.

The resolution of measured energy in EM calorimeter is very good:

$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{b}{E} \oplus 0.7\%$$

where b comes from electronic noise of calorimeter, is about 250 MeV. The resolution of measured energy in hadronic calorimeter is: $\sigma/E = 50\%/\sqrt{E} \oplus 3\%$.

3.2.3 Muon spectrometer

The muon spectrometers (MS) surround the calorimeters and are the outermost ATLAS sub-detectors. A system of three large superconducting air-core toroidal magnets generates a magnetic field providing 1.5 to 5.5 Tm of bending power in the barrel and 1 to 7.5 Tm in the end-cap. Resistive Plate Chambers (RPC, three doublet layers in the barrel) and Thin Gap Chambers (TGC, three triplet and doublet layers in the end-caps) constitutes the muon trigger system for the range $|\eta| < 1.05$ and $1.0 < |\eta| < 2.4$, respectively, with a time resolution on the order of 1 ns. They also give (η, ϕ) position measurements with typical spatial resolutions of 5 – 10 mm up

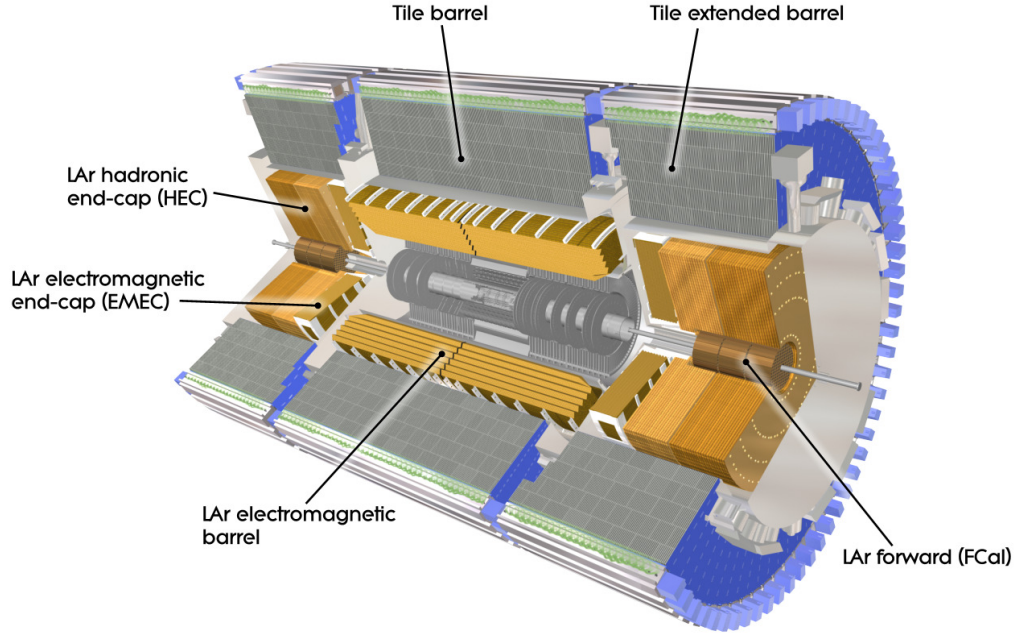


Figure 3.4: Cut-away view of the ATLAS calorimeter system. The electromagnetic (EM) calorimeter is a sampling liquid-argon (LAr) calorimeter with lead absorbers. The hadronic calorimeter is a sampling calorimeter with steel absorbers and active scintillator tiles in the barrel and with copper absorbers and LAr scintillator in the end-cap. The forward calorimeter (FCal) consists of copper/LAr and tungsten/LAr.

to $|\eta| \approx 2.65$, and timing measurements in the non-bending transverse plane. Furthermore, three layers of Monitored Drift Tube chambers (MDT) provide precision momentum measurements of muons with pseudorapidity up to $|\eta| = 2.7$. Each MDT chamber typically has six to eight η measurements along the muon track with a single hit resolution in the precision (rz bending) plane of about $80 \mu\text{m}$. For $|\eta| < 2$, the inner layer is instrumented with a quadruplet of Cathode Strip Chambers (CSC) instead of MDTs. CSC detectors measure position in rz plane with a single hit resolution of

about $60\ \mu\text{m}$ and provide a time measurement with a resolution of $3.6\ \text{ns}$. The relative resolution of measured muon momentum is better than 3% over a wide p_{T} range and up to 10% at $p_{\text{T}} = 1\ \text{TeV}$.

Chapter 4

Data and Monte Carlo samples

4.1 Data samples

The observation of the SM Higgs boson uses pp collision data collected by the ATLAS detector during 2011 and 2012 at center-of-mass energies of $\sqrt{s} = 7$ and 8 TeV with a bunch spacing of 50 ns. Only events taken in stable beam conditions, and in which the trigger system, the tracking devices, the calorimeters and the muon chambers were functioning as expected, are considered in the physics analysis. The resulting effective luminosity for 7 TeV pp data is 4.5 fb^{-1} , and for 8 TeV pp data is 20.3 fb^{-1} . The overall uncertainty on the integrated luminosity for the complete 2011 data set is $\pm 1.8\%$ [86]. The uncertainty on the integrated luminosity for the 2012 data set is $\pm 2.8\%$; this uncertainty is derived following the methodology used in the 2011 data set, from a preliminary calibration of the luminosity scale with beam-separation scans [78, 79] performed in November 2012.

The search for additional heavy scalars uses the pp collision data collected by the ATLAS detector in 2015 and 2016 at a center-of-mass energy of $\sqrt{s} = 13$ TeV with a

bunch spacing of 25 ns. The effective integrated luminosity used in the physics analysis for 2015 and 2016 data set is 36.1 fb^{-1} . The uncertainty on the integrated luminosity of 2015 and 2016 data set is $\pm 3.2\%$. This is derived, following a methodology similar to that detailed in Ref. [82], from a preliminary calibration of the luminosity scale using x - y beam separation scans performed in May 2016.

4.2 Monte Carlo samples

4.2.1 Overview

The ATLAS simulation software chain [87] is generally divided into three steps: (1) the generation of the event for immediate decays, which can be carried out by different generators, following the Les Houches Event file format [88]; (2) the simulation of the detector and soft interactions within the GEANT4 framework [89, 90]; and (3) the digitization of the energy deposited in sensitive regions of the detector into voltages and currents for comparison to the readout of the ATLAS detector. The output of the simulation chain can be presented in a format identical to the output of the ATLAS data acquisition system (DAQ). Thus, both the simulated and observed data can then be run through the same ATLAS trigger and physics reconstruction packages.

In each step, intermediate files are produced and named differently. Files from event generation are usually named as *EVNT*, in which information called “truth” is recorded for each event. The truth information is a history of the interactions from the generator, including incoming and outgoing particles. A record is kept for every particle, whether the particle is to be passed through the detector simulation

or not. Files from the simulation of the ATLAS detector are named as *HITS*, which are then treated as the inputs of the digitization together with additional simulated *HITS* files for minimum bias, beam halo, beam gas and cavern background events . These additional simulated *HITS* files are used to mimic the underlying soft events, particularly the minimum bias files that simulate the “pileup events”, which become more important as the instantaneous luminosity increases. The Monte Carlo (MC) generator used for pileup events is PYTHIA 8.212 [91] with either the A14 [92] set of tuned parameters and NNPDF23 [93] for the parton density functions (PDF) set, or the AZNLO [94] tuned parameters and CTEQ11 [95] PDF when the POWHEG-BOX [96,97] generator is used for the hard process. The simulated events are weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data (pileup reweighting). The properties of the bottom and charm hadron decays are simulated by the EVTGEN v1.2.0 program [98].

4.2.2 Signal Monte Carlo samples

The SM Higgs boson signal is modeled using the POWHEG-BOX generator [96,97, 99,100], which calculates separately the gluon-gluon fusion and weak-boson fusion production with matrix elements up to next-to-leading order (NLO) in the QCD coupling constant. The Higgs boson transverse momentum (p_T) spectrum in the ggF process is re-weighted to follow the calculation of Ref. [101,102], which include QCD corrections up to next-to-next-to-leading order (NNLO) and QCD soft-gluon resummations up to next-to-next-to-leading logarithm (NNLL). The effects of non-zero quark masses are also taken into account [50]. POWHEG-BOX is interfaced to PYTHIA 8 [91,103] for showering and hadronization, which in turn is interfaced to PHOTOS [104,105]

for QED radiative corrections in the final state. PYTHIA 8 is used to simulate the production of a Higgs boson in association with a W or a Z boson (VH) or with a $t\bar{t}$ pair ($t\bar{t}H$). The production of a Higgs boson in association with a $b\bar{b}$ pair ($b\bar{b}H$) is included in the signal yield assuming the same m_H dependence as for the $t\bar{t}H$ process, while the signal efficiency is assumed to be equal to that for ggF production.

In the search for additional scalars, heavy scalar events are produced using the POWHEG [99, 100] generator, which calculates separately the gluon-gluon fusion and vector boson fusion production with matrix elements up to next-to-leading order (NLO) in the QCD coupling constant. The generated events then are interfaced to PYTHIA 8 [91, 103] for decaying the Higgs boson into the four-lepton final state as well as for showering and hadronization. Events from ggF and VBF production are generated separately in the $200 < m_H < 1400$ GeV mass range under the NWA. In addition, events from ggF production with a width of 15% of the scalar mass m_H have been generated with MADGRAPH5_aMC@NLO [77, 106] to validate the signal modeling for LWA. To have better description of the jet multiplicity, MADGRAPH5_aMC@NLO is also used to generate the events of $pp \rightarrow H + \geq 2$ jets at NLO QCD accuracy with the FxFx merging scheme [107], in the Effective Field Theory (EFT) approach ($m_t \rightarrow \infty$). The fraction of the ggF events that enter into the VBF-like category is estimated from MADGRAPH5_aMC@NLO simulation.

4.2.3 Background Monte Carlo samples

The $ZZ^{(*)}$ continuum background from $q\bar{q}$ annihilation is simulated with SHERPA 2.2 [108–110], with the NNPDF3.0 [111] NNLO PDF set for the hard scattering process. NLO accuracy is achieved in the matrix element calculation for 0-, and 1-jet final

states and LO accuracy for 2- and 3-jet final states. The merging of jets from the hard process and parton shower is performed with the SHERPA parton shower [112] using the MEPS@NLO prescription [113]. NLO EW corrections are applied as a function of m_{ZZ} [114, 115]. The EW production of vector boson scattering with two jets down to $O(\alpha_W^6)$ is generated using SHERPA, where the process $ZZZ \rightarrow 4\ell qq$ is also taken into account.

The $gg \rightarrow ZZ^{(*)}$ production is modeled by SHERPA 2.2 at LO in QCD, including the off-shell h contribution and the interference between h and the ZZ background. The k-factor accounting for higher order QCD effects for the $gg \rightarrow ZZ^{(*)}$ continuum production has been calculated for massless quark loops [116–118] in the heavy top-quark approximation [119], including the $gg \rightarrow H^* \rightarrow ZZ$ processes [120]. Based on these studies, a k-factor of 1.7 is used, and a conservative relative uncertainty of 60% on the normalization is applied to both searches.

The WZ background is modeled using POWHEG-BOX v2 interfaced to PYTHIA 8 and EVTGEN v1.2.0. The triboson backgrounds ZZZ , WZZ , and WWZ with four or more prompt leptons are modeled using SHERPA 2.1.1. For the fully leptonic $t\bar{t} + Z$ background, with four prompt leptons coming from the top and Z decays, MADGRAPH5_AMC@NLO is used.

Events containing Z bosons with associated jets are simulated using the SHERPA 2.2.0 generator. Matrix elements are calculated for up to 2 partons at NLO and 4 partons at LO using the COMIX [109] and OPENLOOPS [110] matrix element generators and merged with the SHERPA parton shower [112] using the ME+PS@NLO prescription [113]. The CT10 PDF set is used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The $Z + \text{jets}$ events are normalized to the

NNLO cross sections.

The $t\bar{t}$ background is modeled using POWHEG-BOX v2 interfaced to PYTHIA 6 [121] for parton shower, fragmentation, and the underlying event and to EVTGEN v1.2.0 for properties of the bottom and charm hadron decays.

Chapter 5

Object Reconstruction and Identification

The four-lepton channel has a small event rate but is a relatively clean final state where the signal-to-background ratio, taking the reducible backgrounds into account alone, i.e. ignoring the ZZ background, is above 6 in the observation of a SM Higgs boson analysis; the search for additional heavy scalars in high-mass regions is background free for $m_{4\ell} > 400$ GeV. Significant effort was made to obtain a high efficiency for the reconstruction and identification of electrons and muons, while keeping the loss due to background rejection as small as possible. In particular, this becomes increasingly difficult for electrons as E_T decreases.

Electrons are reconstructed using information from the ID and the electromagnetic calorimeter. For electrons, background discrimination relies on the shower shape information available from the highly segmented LAr EM calorimeter, high-threshold TRT hits, as well as compatibility of the tracking and calorimeter information. Muons are reconstructed as tracks in the ID and MS, and their identification is primarily based on the presence of a matching track or tag in the MS. Finally, jets are reconstructed from clusters of calorimeter cells and calibrated using a dedicated scheme designed

to adjust the energy measured in the calorimeter to that of the true jet energy on average.

5.1 Electron reconstruction and identification

Electron Reconstruction Electron reconstruction in the central region of the ATLAS detector ($|\eta| < 2.47$) starts from energy deposits (seed-clusters) in the EM calorimeter that are matched to reconstructed tracks of charged particles in the inner detector. The η - ϕ space of the EM calorimeter system is divided into a grid of $N_\eta \times N_\phi = 200 \times 256$ towers of size $\Delta\eta^{\text{tower}} \times \Delta\phi^{\text{tower}} = 0.025 \times 0.025$, corresponding to the granularity of the EM accordion calorimeter middle layer. The energy of the calorimeter cells in all longitudinal-depth layers is summed to get the tower energy. Seed clusters of towers with total transverse energy above 2.5 GeV are searched for using a sliding-window algorithm. For each seed cluster passing loose shower-shape requirements, a region-of-interest is defined as a cone of size $\Delta R = 0.3$ around the seed cluster barycenter. An electron is reconstructed if at least one track is matched to the seed cluster. To improve reconstruction efficiency for electrons that undergo significant energy loss due to bremsstrahlung, the track associated to the seed cluster is refitted using a Gaussian-Sum Filter [122]. The electron reconstruction efficiency is 97% for electrons with $E_T = 15$ GeV and 99% at $E_T = 50$ GeV.

Electron Identification Not all objects built by the electron reconstruction algorithms are prompt electrons, which are referred to those coming from W or Z -boson decays. Background objects include hadronic jets as well as the electrons from converted photon decays, Dalitz decays and semi-leptonic heavy-flavor hadron decays.

To distinguish signal electrons from background objects, the variables that describe longitudinal and lateral shapes of the electromagnetic showers in the calorimeters, the properties of the tracks in the ID and the matching between tracks and energy clusters are used in a multivariate technique. Out of different multivariate techniques, the likelihood was chosen for electron identification because of its simple construction. An overall probability for each object to be signal or background is calculated as:

$$d_L = \frac{L_S}{L_S + L_B}, \quad L_{S(B)}(\vec{x}) = \prod_{i=1}^n P_{S(B),i}(x_i)$$

where $\vec{x}$ is the vector of variable values and $P_{S,i}(x_i)$ is the value of the signal probability density function (PDF) of the i_{th} variable evaluated at x_i . In the same way, $P_{B,i}(x_i)$ refers to that for the background. These signal and background PDFs are obtained from data in different $|\eta|$ and E_T bins. By applying a cut on the d_L to match the target signal efficiency expectations, different working points are defined, including “Loose”, “Medium” and “Tight”. The “Loose” criteria is used in this analysis. An insertable b-layer hit or, if no such hit is expected, an innermost pixel hit is required for all electrons. The signal efficiency, including reconstruction and identification, is measured both in data and MC simulation [123] as a function of the transverse energy E_T and the pseudo-rapidity η as shown in Figure 5.1. The disagreement between efficiencies obtained in data and the simulated events is around 5%, due to the known mis-modeling of shower shapes and other identification variables in the simulation. The ratios of the efficiencies measured in data and simulation (so called “scale factors”) and their associated uncertainties are used in this analysis to correct the yields of electrons in simulated events. For electrons with $E_T < 30$ GeV, the total uncertainties on the efficiencies vary from 1% to 3.5%, dominated by statistical uncertainties. For

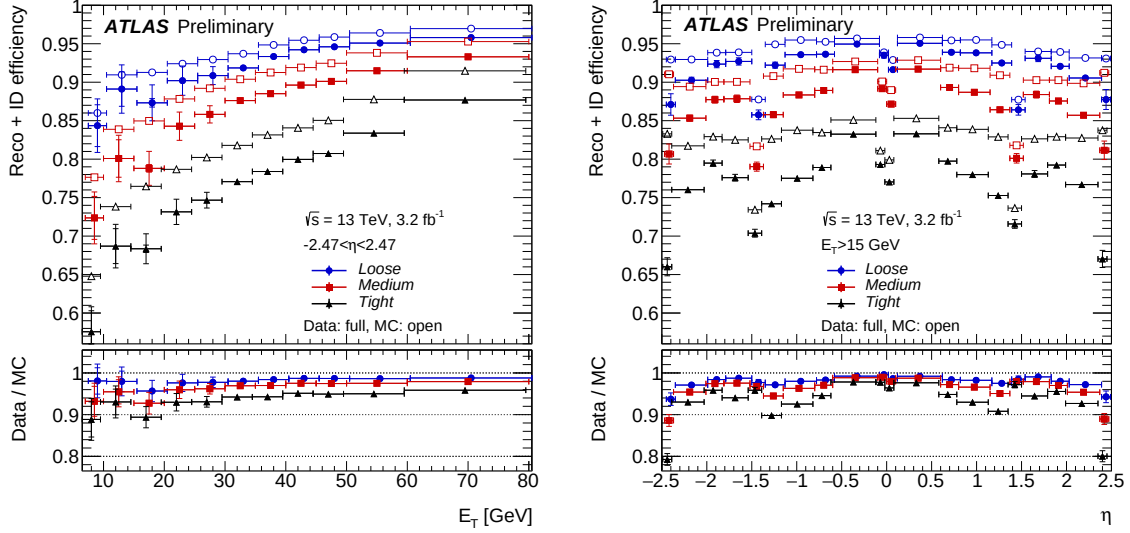


Figure 5.1: Combined electron reconstruction and identification efficiencies in $Z \rightarrow ee$ events as a function of the transverse energy E_T , integrated over the full pseudo-rapidity range (left), and as a function of pseudorapidity η , integrated over the full E_T range (right). The data efficiencies are obtained from the data-to-MC efficiency ratios measured using J/ψ and Z tag-and-probe, multiplied by the MC prediction for electrons from $Z \rightarrow ee$ decays. The uncertainties are obtained with pseudo-experiments, treating the statistical uncertainties from the different (E_T, η) bins as uncorrelated. Two sets of uncertainties are shown: the inner error bars show the statistical uncertainty, the outer error bars show the combined statistical and systematic uncertainty.

electrons with $E_T > 30$ GeV, the total uncertainties are below 1%.

5.2 Muon reconstruction and identification

Muon Reconstruction Muon reconstruction is essentially to reconstruct a track for the muon. Tracks are first reconstructed independently in the ID and MS, and then combined to form the muon tracks that are used in physics analyses. Various algorithms are used to combine MS tracks and ID tracks, resulting in different types of muons [124, 125]:

- **Combined (CB) muons:** a combined track is formed with a global fit using the hits from both the ID and MS subdetectors. Most muons are reconstructed following an outside-in pattern recognition, in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track. An inside-out combined reconstruction, in which ID tracks are extrapolated outward and matched to MS tracks, is used as a complementary approach.
- **Segment tagged (ST) muons:** ST muons are used when muons cross only one layer of MS chambers, failing to form a proper MS track. A track in the ID is identified as an ST muon if the trajectory extrapolated to the MS is associated with at least one local track segment in the precision muon chambers.
- **Calorimeter tagged (CT) muons:** A track in the ID is identified as a CT muon if it matches to an energy deposit in the calorimeters compatible with a minimum-ionizing particle. It's used to recover the efficiency in the region of $|\eta| < 0.1$ where the ATLAS muon spectrometer is only partially instrumented to allow for cabling and services to the calorimeters and inner detector. The

CT-muon identification criteria are optimized for a momentum range of $15 < p_T < 100$ GeV.

- **Extrapolated (ME) muons** (SA): the muon track is reconstructed based only on the MS track and a loose requirement on compatibility with originating from the interaction point. The parameters of the muon track are defined at the interaction point, taking into account the estimated energy loss of the muon in the calorimeters.

Overlaps between different muon types are resolved before producing the collection of muons used in physics analyses. When two muon types share the same ID track, the preferred order of the chosen muon is: CB, ST and CT muons.

Muon Identification Muon identification is performed by applying a set of quality requirements based on the muon types described above. The fake muon mainly comes from pion and kaon decays. CT and ST muons are restricted to the $|\eta| < 0.1$ region while ME muons are allowed only in $2.5 < |\eta| < 2.7$. A set of track quality requirements are applied to the ID tracks to reject poorly reconstructed charged-particle trajectories. Different MS hit requirements are applied to different muon types. ME muons are required to have ≥ 3 precision hits (i.e. MDT or CSC hits) in each of the three layers of the MS. Combined muons are required to have ≥ 3 precision hits in at least two layers of MDT, except for $|\eta| < 0.1$ region where tracks with at least three hits in one single MDT layer are allowed. To suppress muons produced from in-flight decays of hadrons, the difference of measured charge-over-momentum between the ID

and the MS is required to be small:

$$\frac{|q/p_{\text{ID}} - q/p_{\text{MS}}|}{\sqrt{\sigma_{\text{ID}}^2 + \sigma_{\text{ME}}^2}} < 7$$

For muons with $|\eta| < 2.7$ and $5 < p_{\text{T}} < 100$ GeV, the reconstruction and identification efficiency is above 99% for Run 1 data set [124] and close to 99% for Run 2 data set [125].

5.3 Jet reconstruction

Jets are reconstructed at the electromagnetic energy scale (EM scale) with the anti- k_t algorithm [126] and radius parameter $R = 0.4$ using the FASTJET software package [127]. A collection of three-dimensional, massless, positive-energy topological clusters (topo-clusters) [128, 129] made of calorimeter cell energies are used as input to the anti- k_t algorithm. Topo-clusters are built from neighboring calorimeter cells containing a significant energy above a noise threshold that is estimated from measurements of calorimeter electronic noise and simulated pileup noise. The topo-cluster reconstruction algorithm was improved in 2015, particularly preventing topo-clusters from being seeded by the pre-sampler layers. This restricts jet formation from low-energy pileup depositions that do not penetrate the calorimeters [130].

Ref. [130, 131] details the methods used to calibrate the four-momentum of jets in Monte Carlo simulation and in data collected by the ATLAS detector for Run 1 and Run 2 data sets. The jet energy scale (JES) calibration consists of several consecutive stages derived from a combination of MC-based methods and *in situ* techniques. The MC-based calibrations correct the reconstructed jet four-momentum to that found from the simulated stable particles within the jet. The calibrations account for features

of the detector, the jet reconstruction algorithm, jet fragmentation, and the pileup. *In situ* techniques are used to measure the difference in jet response between data and MC simulation, with residual corrections applied to jets in data only.

Fake jets are mainly from beam-induced non- pp collision events [132], cosmic-ray showers produced in the atmosphere overlapping with collision events, and calorimeter noise from large scale coherent noise or isolated pathological cells. To remove these fake jets, the *loose* jet quality criteria, which are designed to provide an efficiency of selecting jets from pp collisions above 99.5% (99.9%) for $p_T > 20(100)$ GeV, as described in Ref. [133], are applied. On the other hand, pileup jets, resulting from multiple pp interactions, are real jets but of no physics interest. They are suppressed by using the jet-vertex-tagger (JVT) [134], which is a likelihood ratio that is based on two variables. One variable is the corrected jet-vertex fraction, which is the fraction of the total momentum of the tracks that are associated with the primary vertex over the total momentum of the tracks inside the jets. The other one is the R_{p_T} , which is defined as the scalar p_T sum of the tracks that are associated with the jet and originate from the hard-scatter vertex divided by the fully calibrated jet p_T . The efficiency of the JVT selecting non-pileup jets is about 97%.

Chapter 6

Analysis Overview

The observation of the SM Higgs boson and the search for additional scalars in the four-lepton final state, reported in this thesis, are the same analyses except that (1) the former focuses on the mass range $[110, 140]$ GeV, while the later searches an resonance in the mass range $[200, 1200]$ GeV. (2) the former uses the LHC Run 1 data sets, sometimes called *Run 1 Higgs analysis*, while the later uses the LHC Run 2 data sets, sometimes called *Run 2 high-mass analysis*. Correspondingly, some trigger and kinematic thresholds were adjusted for the Run 2 analysis, due to the improved object identifications and the increased instantaneous luminosity. The LHC Run 2 data sets were also used for the measurements of the observed SM Higgs boson, but only the results of the measurements are briefly reported in this thesis. (3) the categorization strategy of the four-lepton candidates are different between the Higgs analysis and the high-mass analysis. This chapter summarizes common aspects of the two analyses. Section 6.1 describes the event triggers and Section 6.2 describes the inclusive four-lepton event selections. The background estimation and statistical methodology are detailed in Section 6.3 and Section 6.4.

6.1 Triggers

The LHC has an event rate of 1 GHz (10^9 Hz) but the maximum bandwidth of ATLAS is only 100 kHz, so it's impossible to record all events, and neither is needed. A trigger is a system that uses simple criteria to rapidly decide which events to keep when only a small fraction of the total can be recorded. It is the very first step to distinguish signal events from the backgrounds.

Triggers usually make heavy use of a parallelized design and are divided into *levels*. The idea is that each level selects the data that becomes an input for the following level, which has more time available and more information to make a better decision. In the ATLAS trigger system, the triggers in the first level are called *L1 triggers*, which use the customized hardware processors to make an initial decision. The L1 system suppresses the event rate down to 70 (100) kHz for the Run 1 (Run 2) data sets, and then delivers accepted events to the next level: High Level Trigger system (HLT triggers). In the LHC Run 1 data taking, intermediate-level triggers, *L2 triggers*, was used after the L1 trigger and before the HLT triggers. The HLT system has access to all detector information of all data and can perform reconstruction and identification of the physics objects.

Four-lepton events were selected with the single lepton, and dilepton triggers. The p_T (E_T) thresholds for single-muon (single-electron) triggers increased from 18 to 24 GeV (20 to 24 GeV) between 7 and (8 and 13 TeV) data, in order to cope with the increasing instantaneous luminosity. The dilepton trigger thresholds for 7 TeV data are set at 10 GeV in p_T for muons, 12 GeV in E_T for electrons and (6, 10) GeV for (muon, electron) mixed-flavor pairs. For the 8 TeV and 13 TeV data, the thresholds were raised

to 13 GeV for dimuon trigger, to 12 GeV for the dielectron trigger and (8, 12) GeV for the (muon, electron) trigger; furthermore, a dimuon trigger with different thresholds on the muon p_T , 8 and 18 GeV, was added. Tri-lepton triggers were introduced in 2015 for the four-lepton analysis in Run 2. Tri-lepton triggers require events fulfill any of the following criteria: three electrons with $E_T > 9$ GeV and at least one of them with $E_T > 17$ GeV; or three muons with $p_T > 6$ GeV; or three muons with $p_T > 4$ GeV and at least one of them with $p_T > 18$ GeV. The trigger efficiency for events passing the final selection is above 96% in the 4μ , $2\mu 2e$ channels and close to 100% in the $4e$ and $2e 2\mu$ channel for all data sets.

6.2 Inclusive four-lepton event selections

Each event is required to have at least one vertex with two associated tracks with $p_T > 400$ MeV. As different objects can be reconstructed from the same detector information, a strategy of removing overlapping objects is applied: for an electron and a muon that share the same ID track, if the muon is not a CT muon or an ST muon, the muon is removed otherwise the electron is removed. Also, jets that overlap with electrons or muons are removed.

Four-lepton candidates are formed by selecting a lepton-quadruplet made out of two same-flavor, opposite-sign lepton pairs, and classified into three *channels* based on the lepton flavors: 4μ , $2e 2\mu$ and $4e$. Each electron must satisfy $E_T > 7$ GeV and $|\eta| < 2.47$. The crack region ($1.37 < |\eta| < 1.52$) is included to prevent acceptance loss despite the worse resolution in this region of the calorimeter. The fraction of the events with at least one electron in the crack region is $\sim 18\%$ in the $4e$ channel and $\sim 9\%$ in the $2e 2\mu$ and $2\mu 2e$ channels. CT muons are required to have $p_T > 15$ GeV,

while other types of muons are required to have $p_T > 6$ GeV for the analysis using the LHC Run 1 data sets (*Run 1 analysis*) and $p_T > 5$ GeV for the analysis using the LHC Run 2 data sets (*Run 2 analysis*). The lower threshold for the Run 2 analysis provides an increase in the signal acceptance of about 7% in the 4μ final state for the SM Higgs boson. The three leading leptons, ordered by p_T , must have p_T larger than 20, 15 and 10 GeV respectively. For each quadruplet at most one CT or ST muon or muon in the forward region ($2.5 < |\eta| < 2.7$) is allowed.

At this point, only one quadruplet per channel is selected, by keeping the quadruplet with the lepton pairs closest (leading pair) and second closest (sub-leading pair) to the pole mass of Z boson, with invariant masses referred to as m_{12} and m_{34} . In the selected quadruplet the m_{12} is required to be $50 < m_{12} < 106$ GeV, while the m_{34} is required to be less than 115 GeV and greater than a threshold. The threshold value is 12 GeV for $m_{4\ell} \leq 140$ GeV, rises linearly from 12 to 50 GeV with $m_{4\ell}$ in the interval of [140 GeV, 190 GeV] and stays to 50 GeV for $m_{4\ell} > 190$ GeV.

To reject leptons from J/Ψ , any same-flavor opposite-charge di-lepton pair is required to have invariant mass > 5 GeV. The four leptons in the quadruplet are required to be separated by $\Delta R > 0.1$ for same flavor leptons and $\Delta R > 0.2$ for different flavor leptons.

The Z+jets and $t\bar{t}$ background contributions are reduced by applying impact parameter requirements as well as track- and calorimeter-based isolation requirements to the leptons. The transverse impact parameter significance, defined as the impact parameter calculated with respect to measured beam line position in the transverse plane divided by its uncertainty, $|d_0|/\sigma_{d_0}$, for all muons (electrons) is required to be lower than 3 (5). The normalized track isolation discriminant, defined as the sum

of the transverse momenta of tracks inside a cone of size $\Delta R = 0.3(0.2)$ around the muon (electron) candidate, excluding the lepton track, divided by the lepton p_T , is required to be smaller than 0.15. The larger muon cone size corresponds to that used by the muon trigger. Contributions from pileup are suppressed by requiring tracks in the cone to originate from the primary vertex. To retain efficiency at higher p_T , the track-isolation requirement is reduced to $10 \text{ GeV}/p_T$ for p_T above 33 (50) GeV for muons (electrons).

The relative calorimetric isolation is computed as the sum of the cluster transverse energies E_T in the electromagnetic and hadronic calorimeters, with a reconstructed barycenter inside a cone of size $\Delta R = 0.2$ around the candidate lepton, divided by the lepton p_T . The clusters used for the isolation are the same as those for reconstructing jets. The relative calorimetric isolation is required to be smaller than 0.3 (0.2) for muons (electrons). The measured calorimeter energy around the muon and the cells within 0.125×0.175 in $\eta \times \phi$ around electron barycenter are excluded from the respective sums. The pileup and underlying event contribution to the calorimeter isolation is subtracted event by event [135]. For both the track- and calorimeter-based isolation requirements any contribution arising from other leptons of the quadruplet is subtracted.

For the Run 2 analysis, an additional requirement based on a vertex-reconstruction algorithm, which fits the tracks of the four-lepton candidates under the assumption that they originate from a common vertex, is applied in order to reduce further the Z +jets and $t\bar{t}$ background contributions. A loose cut of $\chi^2/\text{ndof} < 6$ for 4μ and < 9 for the other channels is applied, which leads to a signal efficiency larger than 99% in all channels.

The QED process of radiative photon production in Z boson decays is well modeled by simulation. Some of the final-state radiation (FSR) photons can be identified in the calorimeter and incorporated into the analysis. The strategy to include FSR photons into the reconstruction of Z bosons is the same as in Run 1 [136]. It consists of a search for collinear (for muons) and non-collinear FSR photons (for both muons and electrons) with only one FSR photon allowed per event. After the FSR correction, the lepton four-momenta of both di-lepton pairs are recomputed by means of a Z-mass-constrained kinematic fit. The fit uses a Breit-Wigner Z line shape and a single Gaussian per lepton to model the momentum response function with the Gaussian width set to the expected resolution for each lepton. The Z-mass constraint is applied to both Z candidates, and improves the $m_{4\ell}$ resolution by about 15%.

Events that survive these selections are signal Higgs boson candidates. These events are then classified into different categories to enhance overall search sensitivities, depending on the analysis under consideration.

6.3 Background estimation

6.3.1 Overview

The non-resonant SM $ZZ^{(*)}$ continuum process, whose cross section is about 10 times larger than that of $H \rightarrow ZZ^{(*)}$, is called the *irreducible background*, as it possesses the same final state as the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ process. The irreducible background is modeled by Monte Carlo (MC) simulation with next-to-next-to-leading order QCD corrections and next-to-leading order electroweak corrections [114,137,138] applied as a function of the four-lepton invariant mass. The Z+jets, top-quark pair

and WZ production processes, called *reducible backgrounds*, enter the four-lepton signal region via fake leptons, which are reduced by imposing identification requirements. The reducible backgrounds are important for the observation of the SM Higgs boson but much less important for the search for additional scalars, as they populate mainly the low mass region. The rate of these reducible backgrounds entering the signal region is very low, requiring many simulated events in order to have small statistical uncertainties. To cope with this, data-driven methods are employed to estimate the reducible backgrounds. Minor contamination from tri-bosons and leptonic decay channels of $t\bar{t} + Z$ is modeled by MC simulation.

The reducible backgrounds are estimated separately for the $\ell\ell + ee$ and $\ell\ell + \mu\mu$ channels, where $\ell\ell$ are the two leptons (e or μ) coming from the leading Z-boson, via data-driven methods that follow a general procedure: (a) define control regions (CRs) that target different fake backgrounds by relaxing or inverting isolation/impact parameter significance criteria and/or lepton identification requirements; (b) study background compositions and shapes in these CRs, (c) measure efficiencies for each background source in these CRs or in additional other control regions. (d) extract background events in the signal region from the CRs via transfer factors, which are calculated from MC simulation with corrections that account for the differences between MC simulation and data.

6.3.2 $\ell\ell + \mu\mu$ background

The $\ell\ell + \mu\mu$ reducible background arises mainly from three components: the semileptonic decays of Z +heavy-flavor (HF) jets, the in-flight decays of Z +light-flavor (LF) jets, and the decays of $t\bar{t}$ process. A reference control region that is enriched in

the three components with good statistics is defined by applying the analysis event selections, except for the isolation and impact parameter requirements that are applied on the two muons in the subleading dilepton pair. The number of events for each background component in the reference control region is estimated from an unbinned maximum likelihood fit, performed simultaneously to four orthogonal control regions, each of them providing information on one or more of the background components. Finally, the background estimates in the reference control region are extrapolated to the signal region via MC-based transfer factors.

The control regions used in the maximum likelihood fit are designed to be orthogonal and to minimize the contamination from the Higgs boson signal and the $ZZ^{(*)}$ background. The four control regions are:

1. **Inverted criteria on impact parameter significance.** Candidates are selected following the standard analysis selections, but (1) without applying the isolation requirement to the muons of the subleading dilepton and (2) requiring that at least one of the two muons fails the impact parameter significance selection. For the Run 2 analysis, the vertex requirement is not applied to gain statistics. As a result, this control region is enriched in the Z +HF and $t\bar{t}$ events.
2. **Inverted criteria on isolation:** Candidates are selected following the standard analysis selections, but requiring that at least one of the muons of the subleading dilepton fails the isolation requirement. For the Run 2 analysis, the vertex cut is applied to reject the contamination from Z +HF and $t\bar{t}$. This control region is enriched in the Z +LF events and $t\bar{t}$ events.
3. **$e\mu$ leading dilepton ($e\mu + \mu\mu$):** Candidates are selected following the standard

analysis selections, but requiring the leading dilepton to be an electron-muon pair. For the Run 2 analysis, the vertex requirement is not applied. Moreover, the impact parameter and isolation requirements are not applied to the two muons of the subleading dilepton. This control region is dominated by $t\bar{t}$ events.

4. **Same-sign (SS) subleading dilepton:** Candidates are selected following the standard analysis selections, but for the subleading dilepton neither isolation nor impact parameter significance requirements are applied and the two muons are required to have the same charge (SS). This SS control region is not dominated by a specific background.

The residual contributions from $ZZ^{(*)}$ and WZ production are estimated for each control region from MC simulation. In the unbinned likelihood fit, the observable is the invariant mass of the leading dilepton pair (m_{12}), which peaks at the Z mass for the Z +jets events and has a broad distribution for the $t\bar{t}$ events. The m_{12} distribution is parameterized by a second-order Chebyshev polynomial for the $t\bar{t}$ events and a Breit-Wigner function convolved with a Crystal Ball function for the Z +jets events. The parameters of these functions are derived from simulation with MC statistic uncertainties implemented as nuisance parameters. The results of the combined fit in the four control regions are shown in Figure 6.1 for the Run 1 data sets and in Figure 6.2 for the Run 2 data sets, along with the individual background components, while the event yields in the reference control region are summarized in Table 6.1.

Finally the estimated number of events for each contribution in the reference control region is extrapolated to the signal region by multiplying each background component by the probability of satisfying the isolation and impact parameter signif-

Table 6.1: Data-driven $\ell\ell + \mu\mu$ background estimates for the Run 1 and Run 2 data sets, expressed as yields in the reference control region, for the combined fits of four control regions. The statistical uncertainties are also shown.

	Z +heavy-flavor jets	Z +light-flavor jets	Total Z +jets	$t\bar{t}$
Run 1	159 ± 20	49 ± 10	208 ± 22	210 ± 12
Run 2	908 ± 52	50 ± 21	958 ± 57	918 ± 23

ificance requirements, estimated from the relevant simulated samples. The systematic uncertainty in these transfer factors stems mostly from the size of the simulated MC samples. It is 6% for Z +heavy-flavor jets, 60% for Z +light-flavor jets and 16% for $t\bar{t}$ for the Run 1 analysis; and it is 12% for Z +heavy-flavor jets, 70% for Z +light-flavor jets, and 10% for $t\bar{t}$ for the Run 2 analysis. Furthermore, these simulation-based transfer factors are validated with data using muons accompanying $Z \rightarrow \ell\ell$ candidates, where the leptons composing the Z boson candidate are required to satisfy isolation and impact parameter criteria. Events with four leptons, or with an opposite-sign dimuon with mass less than 5 GeV, are excluded. Based on the data/simulation agreement of the efficiencies in this control region, an additional systematic uncertainty of about 2% is added for the Run 1 analysis. For the Run 2 analysis, the mismodeling of the efficiency of isolation for a light-flavor jet in simulation is observed, resulting in a conservative 100% systematic uncertainty for the Z +light-flavor jets.

The reducible background estimates in the signal region in the full $m_{4\ell}$ mass range are given in Table 6.2, separately for the $\sqrt{s} = 7$ TeV, 8 TeV and 13 TeV data. The uncertainties are separate into statistical and systematic contributions, where in the latter the transfer factor uncertainty and the fit systematic uncertainty are included.

Table 6.2: Estimates for the $\ell\ell + \mu\mu$ background in the signal region for the full $m_{4\ell}$ mass range for the $\sqrt{s} = 7$ TeV, 8 TeV and 13 TeV data. The Z +jets and $t\bar{t}$ background estimates are data-driven and the WZ contribution is from simulation. The statistical and systematic uncertainties are presented in a sequential order. The statistical uncertainty for the WZ contribution is negligible.

	4μ	$2e2\mu$
$\sqrt{s} = 7$ TeV		
Z +jets	$0.42 \pm 0.21 \pm 0.08$	$0.29 \pm 0.14 \pm 0.05$
$t\bar{t}$	$0.081 \pm 0.016 \pm 0.021$	$0.056 \pm 0.011 \pm 0.015$
WZ	0.08 ± 0.05	0.19 ± 0.10
$\sqrt{s} = 8$ TeV		
Z +jets	$3.11 \pm 0.46 \pm 0.43$	$2.58 \pm 0.39 \pm 0.43$
$t\bar{t}$	$0.51 \pm 0.03 \pm 0.09$	$0.48 \pm 0.03 \pm 0.08$
WZ	0.42 ± 0.07	0.44 ± 0.06
$\sqrt{s} = 13$ TeV		
Z +jets	$4.44 \pm 0.30 \pm 1.05$	$2.64 \pm 0.22 \pm 0.36$
$t\bar{t}$	$0.65 \pm 0.02 \pm 0.17$	$1.70 \pm 0.05 \pm 0.35$
WZ	0.53 ± 0.30	0.38 ± 0.24

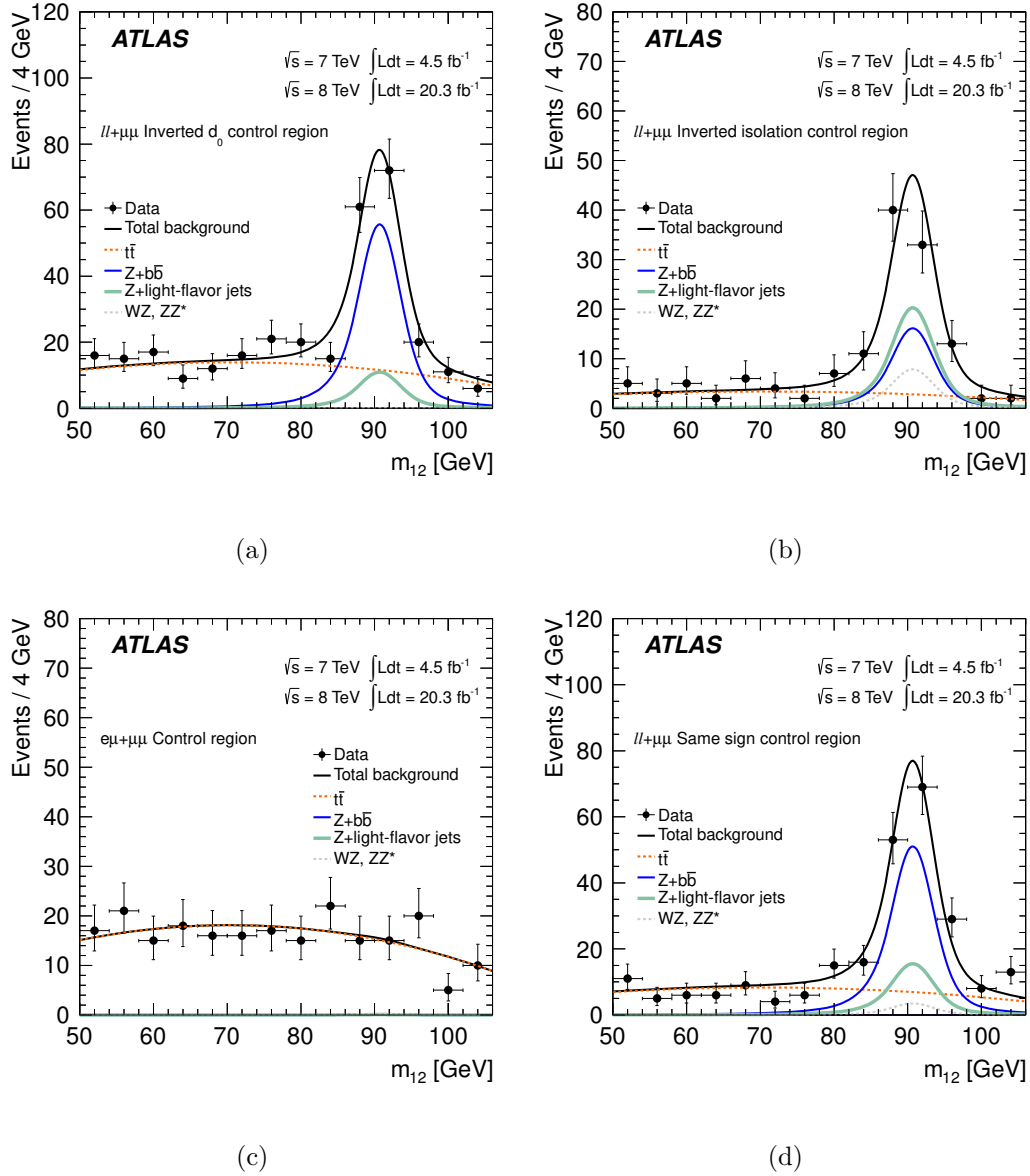


Figure 6.1: The observed m_{12} distributions (filled circles) and the results of the maximum likelihood fit are presented for the four control regions using the Run 1 data sets: (a) inverted criteria on impact parameter significance, (b) inverted criteria on isolation, (c) $e\mu$ leading dilepton, (d) same-sign subleading dilepton. The fit results are shown for the total background (black line) as well as the individual components: Z +jets decomposed into $Z + t\bar{b}$, i.e. Z +heavy-flavor jets (blue line) and the Z +light-flavor jets (green line), $t\bar{t}$ (dashed red line), and the combined WZ and $ZZ^{(*)}$ (dashed gray line), where the WZ and ZZ contributions are estimated from simulation.

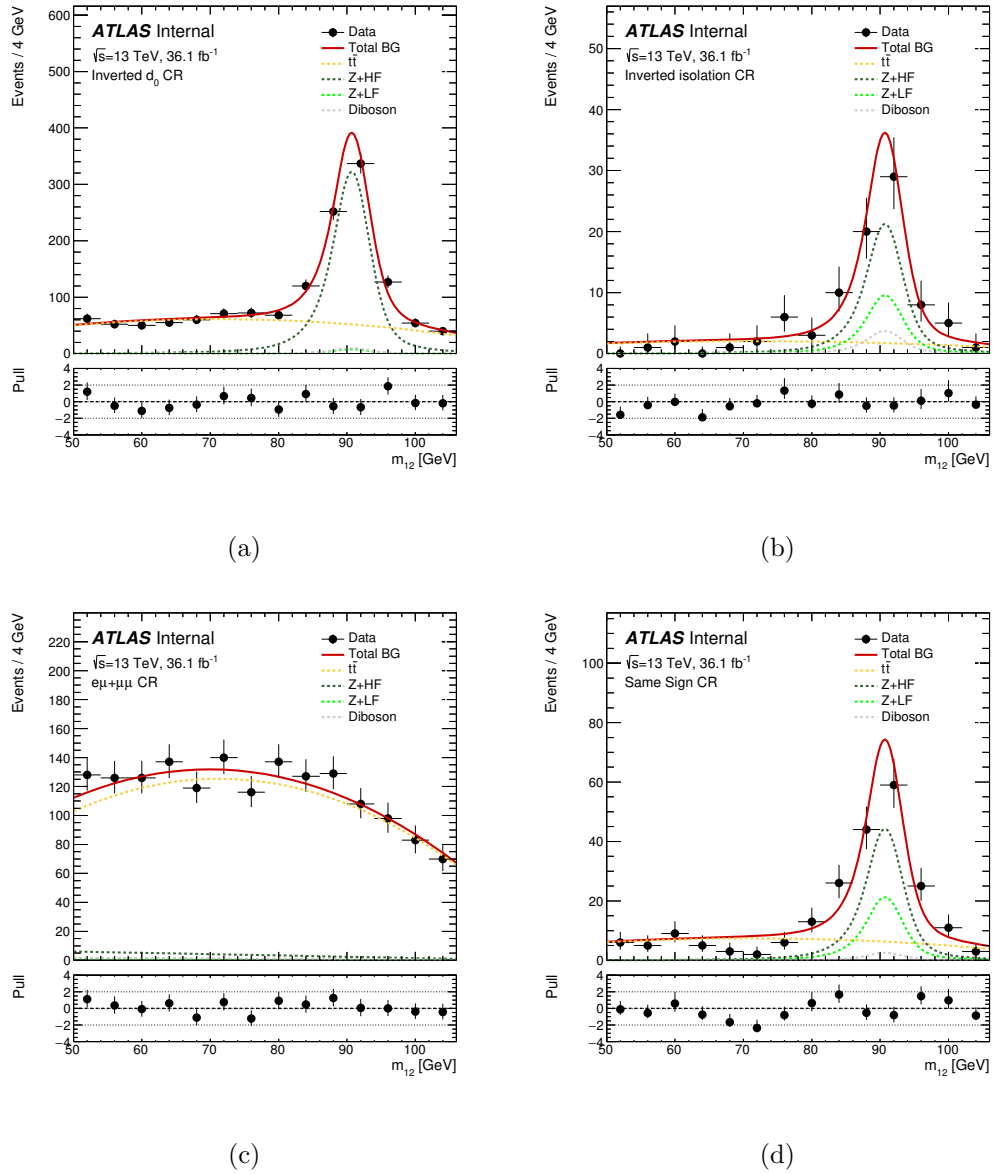


Figure 6.2: The observed m_{12} distributions (filled circles) and the results of the maximum likelihood fit are presented for the four control regions using the Run 2 data sets: (a) inverted criteria on impact parameter significance, (b) inverted criteria on isolation, (c) $e\mu$ leading dilepton, (d) same-sign subleading dilepton. The fit results are shown for the total background (black line) as well as the individual components: Z +jets decomposed into $Z + t\bar{b}$, i.e. Z +heavy-flavor jets (blue line) and the Z +light-flavor jets (green line), $t\bar{t}$ (dashed red line), and the combined WZ and $ZZ^{(*)}$ (dashed gray line), where the WZ and ZZ contributions are estimated from simulation.

6.3.3 $\ell\ell + ee$ background

The $\ell\ell + ee$ reducible background originates mainly from light-flavor jets (f), converted photons (γ) and heavy-flavor semileptonic decays (q). A control region enriched in events associated with each of these sources is defined, namely the $3\ell + X$ control region, allowing data-driven classification of reconstructed events into matching sources. The efficiencies needed to extrapolate the different background sources from the control region into the signal region are obtained separately for each of the f , γ , q background sources, in p_T and η bins from simulation. These simulation-based efficiencies are corrected to the ones measured in data using another control region, denoted as $Z + X$. The $Z + X$ control region has a leading lepton pair compatible with the decay of a Z boson, passing the full event selection. And the additional object (X) satisfies the relaxed requirements as for the X in the $3\ell + X$ control region.

Candidates in the $3\ell + X$ control region are selected by following the standard analysis selections, but requiring relaxed selections on the lowest- E_T electron: only a track with a minimum number of silicon hits which matches a cluster is required. The electron identification and isolation/impact parameter significance selection criteria are not applied. For the Run 2 analysis, the vertex and impact parameter significance requirements are applied to reject the q background source, which is then estimated from MC simulation. In addition, the subleading electron pair is required to have the same sign for both charges (SS) to suppress contributions from $ZZ^{(*)}$ background. A residual $ZZ^{(*)}$ component with a magnitude of 5% of the background estimate survives the SS selection, and is subtracted from the final estimate based on MC simulation.

The yields of different background sources are extracted from a template fit. For the Run 1 analysis, two observables are used in the fit: the number of hits in the innermost layer of the pixel detector ($n_{\text{hits}}^{\text{B-layer}}$) and the ratio of the number of high-threshold to low-threshold TRT hits (r_{TRT}), allowing separation of the f , γ and q components, since most photons convert after the innermost pixel layer, and hadrons faking electrons have a lower r_{TRT} compared to conversions and heavy-flavor electrons. For the Run 2 analysis, since the q component is removed by applying the impact parameter significance requirements, only the number of pixel hits (n_{InnerPix}) is used, defined as the number of IBL hits, or the number of hits on the next-to-innermost pixel layer when such hits are expected due to a dead area of the IBL. The fitted results are shown in Figure 6.3 for the Run 1 data sets and in Figure 6.4 for the Run 2 data sets. The *sPlot* method [139] is used to unfold the contributions from the different background sources as a function of electron p_{T} .

To extrapolate the f , γ and q components (the q component is only presented in the Run 1 analysis) from the $3\ell + X$ control region to the signal region, the efficiency for the different components to satisfy all selection criteria is obtained from the $Z + X$ simulation, and adjusted to match the measured efficiency in data. The systematic uncertainty is dominated by the simulation efficiency corrections, corresponding to 30%, 20%, 25% uncertainties for the f , γ , q , respectively, for the Run 1 analysis, and about 23% uncertainties for the f and γ for the Run 2 analysis. The final results for reducible backgrounds in the $2\mu 2e$ and $4e$ channels are given in Table 6.3 for the Higgs analysis and the high-mass analysis.

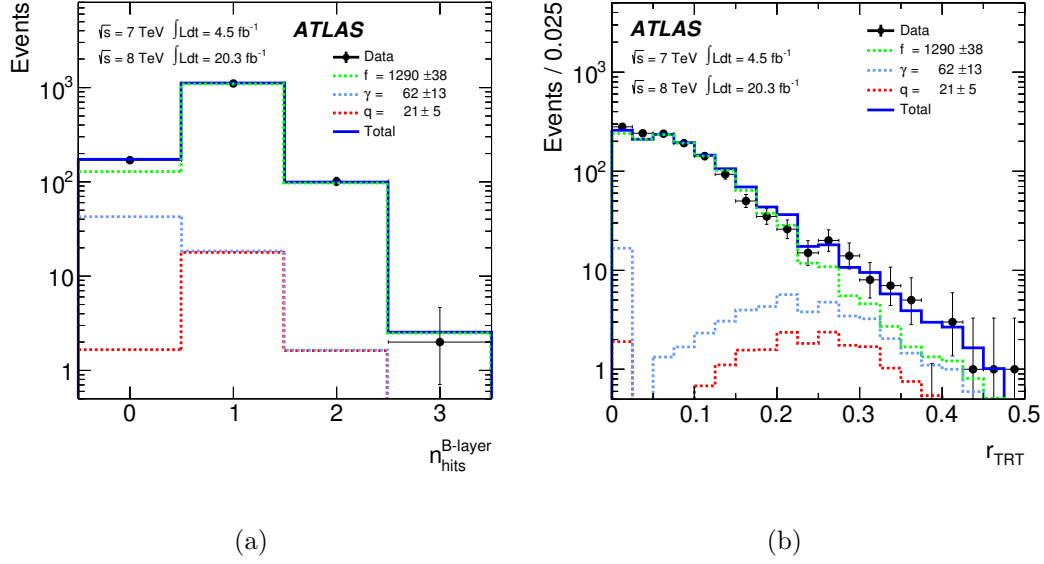
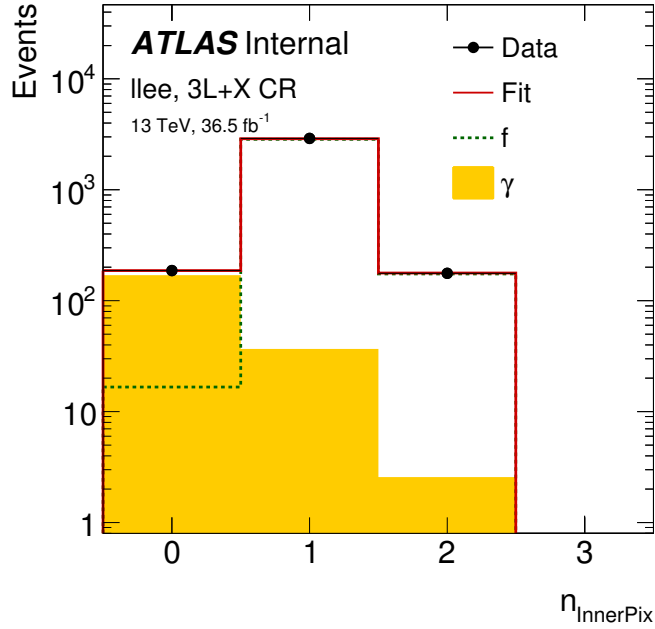


Figure 6.3: The results of a simultaneous fit to (a) $n_{\text{hits}}^{\text{B-layer}}$, the number of hits in the innermost pixel layer, and (b) r_{TRT} , the ratio of the number of high-threshold to low-threshold TRT hits, for the background sources in the $3\ell + X$ control region. The fit is performed separately for the $2\mu 2e$ and $4e$ channels and summed together in the present plots. The data are represented by the filled circles. The sources of background electrons are denoted as light-flavor jets faking an electron (f , green dashed histogram), photon conversion (γ , blue dashed histogram) and electrons from heavy-flavor quark semileptonic decays (q , red dashed histogram). The total background is given by the solid blue histogram.



(a)

Figure 6.4: The results of a fit to n_{InnerPix} , the number of IBL hits, or the number of hits on the next-to-innermost pixel layer when such hits are expected due to a dead area of the IBL, for background sources in the $3\ell + X$ control region. The fit is performed separately for the $2\mu 2e$ and $4e$ channels and summed together in the present plots. The data are represented by the filled circles. The sources of background electrons are denoted as light-flavor jets faking an electron (f , green dashed histogram) and photon conversion (γ , yellow filled histogram). The number of electrons from semileptonic decays of heavy-flavor quarks are negligibly small. The total background is given by the solid red histogram.

Table 6.3: The fit results for the $3\ell + X$ control region, the extrapolation factors and the signal region yields for the reducible $\ell\ell + ee$ background. The sources of background electrons are denoted as light-flavor jets faking an electron (f), photon conversion (γ) and electrons from heavy-flavor quark semileptonic decays (q). The second column gives the fit yield of each component in the $3\ell + X$ control region. The corresponding extrapolation efficiency and signal region yield are in the next two columns. The background values represent the sum of the $2\mu 2e$ and $4e$ channels. The uncertainties are a combination of the statistical and systematic uncertainties.

Type	Fit yield in control region	Extrapolation factor	Yield in signal region
$\sqrt{s} = 7 \text{ TeV}$			
f	391 ± 29	0.010 ± 0.001	3.9 ± 0.9
γ	19 ± 9	0.10 ± 0.02	2.0 ± 1.0
q	5.1 ± 1.0	0.10 ± 0.03	0.51 ± 0.15
$\sqrt{s} = 8 \text{ TeV}$			
f	894 ± 44	0.0034 ± 0.0004	3.1 ± 1.0
γ	48 ± 15	0.024 ± 0.004	1.1 ± 0.6
q	18.3 ± 3.6	0.10 ± 0.02	1.8 ± 0.5
$\sqrt{s} = 13 \text{ TeV}$			
f	3075 ± 56	0.0020 ± 0.0004	5.68 ± 1.24
γ	208 ± 17	0.0071 ± 0.0014	1.34 ± 0.44
q	(MC-based estimation)		6.34 ± 1.93

6.4 Statistical methodology

The statistical interpretation of an analysis can be summarized by either a *p-value* for discovery purposes or an *upper limit* on one or more parameters of the signal model under test. The *p-value* is defined as the probability, under an assumption, of finding data of equal or greater incompatibility with the predictions of the assumption. The measure of incompatibility is based on a *test statistic*, such as the number of events in the signal region. When the look-elsewhere effect [140] is taken into account in calculating a *p-value*, the *p-value* is called *global p-value*, otherwise it is called *local p-value*. An equivalent formulation of *p-value* in terms of the number of standard deviation (σ), Z , referred to as the *significance*, is defined such that a Gaussian distributed variable found Z standard deviation(s) above its mean has an upper-tail probability equal to the *p-value*. That is $Z = \Phi^{-1}(1 - p)$, where Φ^{-1} is the quantile (inverse of the cumulative distribution) of the standard Gaussian. For example, a significance of 5σ ($Z = 5$) equals to a *p-value* of 2.866×10^{-7} . The statistical treatment follows the procedure for the Higgs-boson search combination [141,142], and is implemented with RooFit [143] and RooStats [144].

Construction of likelihood The test statistic employed for hypothesis testing and limit setting is the profiled likelihood ratio $\Lambda(\mu)$:

$$\Lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\alpha))}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})} \quad (6.1)$$

where the μ are the parameters of interest, $\boldsymbol{\theta}$ are the nuisance parameters that represent systematic uncertainties estimated in auxiliary measurements. The $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ refer

to the unconditional maximum likelihood estimators of μ and $\boldsymbol{\theta}$, respectively, and the $\hat{\boldsymbol{\theta}}(\mu)$ refers to the best fitted values of $\boldsymbol{\theta}$ when the parameters of interest are set to μ as constant values. The Neyman-Pearson lemma [145] indicates that the test statistic of likelihood offers good separation power for any type of hypotheses.

The final likelihood $\mathcal{L}$ is a product of the likelihood for each category $\mathcal{L}_i$, each $\mathcal{L}_i$ consisting of a Poisson term, likelihood functions and Gaussian constraint terms:

$$\begin{aligned}\mathcal{L} &= \prod_i^c \mathcal{L}_i \\ \mathcal{L}_i &= \text{Poisson}(n_i | S^i(\mu, \boldsymbol{\theta}) + B^i(\boldsymbol{\theta})) \\ &\quad \times \left[\prod_{j=1}^{n_i} \frac{S(\mu, \boldsymbol{\theta}) f_S^i(\mathbf{x}_j; \boldsymbol{\theta}) + B^i f_B^i(\mathbf{x}_j; \boldsymbol{\theta})}{S^i(\mu, \boldsymbol{\theta}) + B^i(\boldsymbol{\theta})} \right] \cdot \text{Gauss}(\boldsymbol{\theta}; 0, 1)\end{aligned}\tag{6.2}$$

where S^i and B^i are the expected number of signal and background events in category i . $f_X(\mathbf{x}; \boldsymbol{\theta})$, the probability density function of the observable $\mathbf{x}$, usually depends on some systematic uncertainties $\boldsymbol{\theta}$, such as lepton energy/momentum scale uncertainties. The expected number of signal events is parameterized as:

$$S = \mu \times \sigma \times \mathcal{BR}_p \times \mathcal{BR}_d \times A \times C \times \int \mathcal{L} \times (1 + \epsilon(\boldsymbol{\theta}))\tag{6.3}$$

where μ is the signal strength, σ is the total cross section; $A \times C$ is the acceptance times efficiency; $\int \mathcal{L}$ is the integrated luminosity of the dataset; $\mathcal{BR}_p$ is the branching ratio of $H \rightarrow ZZ^{(*)}$ and $\mathcal{BR}_d$ is that of $ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$. The advantage of factorizing the two branching ratios is that for the search for additional scalars, $\mathcal{BR}_p$ depends on the nature of the additional scalars but $\mathcal{BR}_d$ is known from the SM when both ZZ are on-shell. $\mathcal{BR}_d(ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-) = 0.00452$, where ℓ stands for a e or μ , allowing for setting upper limits on $\sigma \times \mathcal{BR}_p$. The term $\epsilon(\boldsymbol{\theta})$ represents the relative impact of systematic uncertainties $\boldsymbol{\theta}$.

Probability distribution function of the likelihood Because only upwards deviation is of physical interests, equation 6.1 is extended to:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\Lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(\mu, \boldsymbol{\theta})}{\mathcal{L}(0, \hat{\boldsymbol{\theta}})} & \hat{\mu} < 0, \\ -2 \ln \frac{\mathcal{L}(\mu, \boldsymbol{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})} & 0 \leq \hat{\mu} < \mu, \\ 0 & \hat{\mu} > \mu. \end{cases} \quad (6.4)$$

for setting limits and extended to:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\Lambda}(\mu) & \hat{\mu} \geq \mu \\ 0 & \hat{\mu} < \mu \end{cases} \quad (6.5)$$

for calculating p -value.

Based on the results due to Wilks [146] and Wald [147], Ref. [148] finds the probability distribution function of the profiled likelihood ratio can be approximated by a χ^2 function with the same number of degrees of freedom as the one in the parameters of the interest. Consequently, the significance of the deviation of data from background-only expectations can be obtained simply by $Z_\mu = \Phi^{-1}(1 - p_\mu) = \sqrt{q_\mu}$.

The limit setting is based on the CL_s prescription [149], which protects from excluding the regions that the analysis is not sensitive to. The confidence level CL_s is defined as $CL_s = \frac{p_{s+b}}{1-p_b}$, where p_{s+b} is the p -value of signal plus background Asimov data¹, and p_b is the p -value of background-only Asimov data. In general, the probability distribution function of $\tilde{q}_\mu$ for signal plus background and background-only asimov data follows the asymptotic assumption [148], but the assumption fails if the number of expected background events is too small, for example less than one. Therefore, the

¹ a single representative data set of the ensemble of simulated data sets.

probability distribution functions constructed from pseudo experiments are used as a cross check.

Chapter 7

The observation of the SM Higgs boson in the $\ell^+\ell^-\ell^+\ell^-$ final state

7.1 Overview

The search for the SM Higgs boson in the $\ell^+\ell^-\ell^+\ell^-$ final state in ATLAS was first reported in Ref. [150] in September 2011, using an integrated luminosity of 2.1 fb^{-1} pp collision data at $\sqrt{s} = 7 \text{ TeV}$. The SM Higgs boson was excluded at 95% confidence level (CL) in the mass ranges 191–197, 199–200 and 214–224 GeV. Five months later (February 2012), this search was updated in Ref. [151] with an integrated luminosity of 4.8 fb^{-1} pp collision data at $\sqrt{s} = 7 \text{ TeV}$. The SM Higgs boson was excluded at 95% CL in the mass ranges 134–156, 182–233 and 256–265 GeV. In the same paper, three excesses were reported with local significances of 2.1, 2.2 and 2.1 standard deviations at 125 GeV, 244 GeV and 500 GeV, respectively. Another five months later (July 2012), ATLAS reported the observation of a new particle in the combined searches for the SM Higgs boson, where the four-lepton analysis was the most sensitive channel for a

125 GeV SM Higgs boson with an expected significance of 2.7 standard deviations [12]. Although the SM Higgs boson was discovered by the combination of different decay channels, it is of great interest to discover the Higgs boson independently in the four-lepton final state alone. After the discovery of a new particle, the four-lepton analysis was fully optimized to search for and measure a SM Higgs boson with a mass of about 125 GeV. Section 7.2 describes the categorization strategies that are designed to probe different Higgs production modes, thus enhancing the overall sensitivities. Background estimates are presented in Section 7.3. Since the mass of the Higgs boson was known [12,152] and other properties could be simulated, the Run 1 Higgs analysis employed multivariate techniques in most categories to distinguish either signal from $ZZ^{(*)}$ background or one production mode from others, as presented in Section 7.4. Furthermore, this analysis conducted two-dimensional fits in some categories to reduce the statistical uncertainties. Section 7.5 discusses the signal and background modeling in each category, followed by the systematic uncertainties in Section 7.6. Final results based on the LHC Run 1 data sets are then presented in Section 7.7.

7.2 Event categorization

The four-lepton candidates passing the selections described in Chapter 6 are classified into one of these categories: VBF enriched, VH-hadronic enriched, VH-leptonic enriched or ggF enriched. A schematic view of the event categorization strategy is shown in Fig. 7.1.

The VBF enriched category is defined by events with two high- p_T jets, which are required to have $p_T > 25(30)$ GeV for $|\eta| < 2.5$ ($2.5 < |\eta| < 4.5$). If more than two jets fulfill these requirements, the two highest- p_T jets are selected as VBF jets.

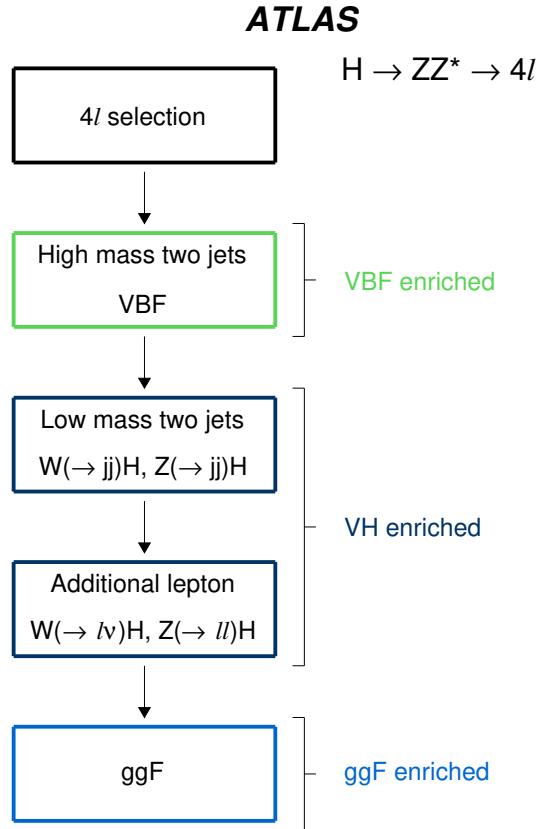


Figure 7.1: Schematic view of the event categorization. Events are required to pass the four-lepton selections, and then they are classified into one of the four categories which are checked sequentially: VBF enriched, VH-hadronic enriched, VH-leptonic enriched, or ggF enriched.

The event is assigned to the VBF enriched category if the invariant mass of the dijet system, m_{jj} , is greater than 130 GeV, leading to a signal efficiency of approximately 55%. This category has a considerable contamination from ggF events, with 54% of the expected events in this category arising from ggF production.

Events that do not satisfy the VBF enriched criteria are considered for the VH-hadronic enriched category. The same jet-related requirements are applied but with $40 < m_{jj} < 130$ GeV. Moreover, the candidate has to fulfill a requirement on the output weight of a specific multivariate discriminant, presented in Section 7.4. The signal efficiency for requiring two jets is 48% for VH and applying the multivariate discriminant brings the overall signal efficiency to 25%.

Events failing to satisfy the above criteria are next considered for the VH-leptonic enriched category. Events are assigned to this category if there is an extra lepton (e or μ), in addition to the four-leptons forming the Higgs boson candidate, with $p_T > 8$ GeV and satisfying the same lepton requirements. The signal efficiency for the extra vector boson for the VH-leptonic enriched category is around 90% (100%) for the W (Z), where the Z has two leptons which can pass the extra lepton selection.

Finally, events that are not assigned to any of the above categories are associated with the ggF enriched category. Table 7.4 shows the expected yields for Higgs boson production in each category from each of the production mechanism, for $m_H = 125$ GeV and 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV.

7.3 Background estimation

The methodologies used to estimate the background yields are described in Chapter 6.3. For the reducible backgrounds, the fraction of background in each category

Table 7.1: The expected number of events in each category (VBF enriched, VH-hadronic enriched, VH-leptonic enriched, ggF enriched), after all analysis criteria are applied, for each signal production mechanism (ggF/ $b\bar{b}H/t\bar{t}H$, VBF, VH) at $m_H = 125$ GeV, for 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV. The requirement $m_{4\ell} > 110$ GeV is applied

Category	$gg \rightarrow H, q\bar{q} \rightarrow b\bar{b}H/t\bar{t}H$	$qq' \rightarrow Hqq'$	$q\bar{q} \rightarrow VH$
$\sqrt{s} = 7$ TeV			
VBF enriched	0.13 ± 0.04	0.137 ± 0.009	0.015 ± 0.001
VH-hadronic enriched	0.053 ± 0.018	0.007 ± 0.001	0.038 ± 0.002
VH-leptonic enriched	0.005 ± 0.001	0.0007 ± 0.0001	0.023 ± 0.002
ggF enriched	2.05 ± 0.25	0.114 ± 0.005	0.067 ± 0.003
$\sqrt{s} = 8$ TeV			
VBF enriched	0.13 ± 0.04	0.69 ± 0.05	0.10 ± 0.01
VH-hadronic enriched	1.2 ± 0.4	0.030 ± 0.004	0.21 ± 0.01
VH-leptonic enriched	0.41 ± 0.14	0.0009 ± 0.0002	0.13 ± 0.01
ggF enriched	12.0 ± 1.4	0.52 ± 0.02	0.37 ± 0.02

is evaluated using simulation. Applying these fractions to the background yields of $\ell\ell + \mu\mu$ described in Section 6.3.2 and that of $\ell\ell + ee$ in Section 6.3.3 gives the reducible background estimates per category shown in Table 7.2.

7.4 Multivariate techniques

The analysis sensitivity is improved by employing three multivariate discriminants to distinguish between different classes of four-lepton events: one to separate the Higgs boson signal from the $ZZ^{(*)}$ background in the inclusive analysis, and two to separate the VBF- and VH-produced Higgs boson signal from the ggF-produced Higgs boson signal in the VBF enriched and VH-hadronic enriched categories. These discriminants are based on boosted decision trees (BDTs) [153].

Table 7.2: Summary of the reducible-background estimates for the data recorded at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV for the full $m_{4\ell}$ mass range. The quoted uncertainties include the combined statistical and systematic components.

Channel	ggF enriched	VBF enriched	VH-hadronic enriched	VH-leptonic enriched
$\sqrt{s} = 7$ TeV				
$\ell\ell + \mu\mu$	0.98 ± 0.32	0.12 ± 0.08	0.04 ± 0.02	0.004 ± 0.004
$\ell\ell + ee$	5.5 ± 1.2	0.51 ± 0.6	0.20 ± 0.16	0.06 ± 0.11
$\sqrt{s} = 8$ TeV				
$\ell\ell + \mu\mu$	6.7 ± 1.4	0.6 ± 0.6	0.21 ± 0.13	0.003 ± 0.003
$\ell\ell + ee$	5.1 ± 1.4	0.5 ± 0.6	0.19 ± 0.15	0.06 ± 0.11

BDT for $ZZ^{(*)}$ background rejection The differences in the kinematics of the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ decay and the $ZZ^{(*)}$ background are incorporated into a BDT discriminant ($\text{BDT}_{ZZ^{(*)}}$). The training is done using fully simulated $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ signal events, generated with $m_H = 125$ GeV for ggF production and $q\bar{q} \rightarrow ZZ^{(*)}$ background events. Only events satisfying the inclusive event selection requirements and with $115 < m_{4\ell} < 130$ GeV are considered. This range contains 95% of the signal and is asymmetric around 125 GeV to include the residual effects of FSR and bremsstrahlung. The discriminating variables used in the training are the transverse momentum of the four-lepton system ($p_T^{4\ell}$); the pseudorapidity of the four-lepton system ($\eta^{4\ell}$), correlated to the $p_T^{4\ell}$; and a matrix-element-based kinematic discriminant ($D_{ZZ^{(*)}}$). The discriminant $D_{ZZ^{(*)}}$ is defined as

$$D_{ZZ^{(*)}} = \ln \left(\frac{|\mathcal{M}_{\text{sig}}|^2}{|\mathcal{M}_{ZZ}|^2} \right)$$

where $\mathcal{M}_{\text{sig}}$ corresponds to the matrix element for the signal process, while $\mathcal{M}_{ZZ}$ is the matrix element for the $ZZ^{(*)}$ background process. The matrix elements for both signal and background are computed at leading order using MADGRAPH [77]. The

matrix element for the signal is evaluated according to the SM hypothesis of a scalar boson with spin-parity $J^P = 0^+$ [154] and under the assumption that $m_H = m_{4\ell}$. Figures 7.2(a)–7.2(c) show the distributions of the variables used to train the $\text{BDT}_{\text{ZZ}^{(*)}}$ classifier for the signal and the $\text{ZZ}^{(*)}$ background. The separation between a SM Higgs signal and the $\text{ZZ}^{(*)}$ background can be seen in Fig. 7.2(d).

As discussed in Sec. 7.5, the $\text{BDT}_{\text{ZZ}^{(*)}}$ output is exploited in the two-dimensional model built to measure the Higgs boson mass, the inclusive signal strength and the signal strength in the ggF enriched category. The signal strength μ is defined as the ratio of the measured Higgs boson production cross section times the branching ratio over that predicted by the SM. Therefore, by definition, the SM predicted value of the signal strength for the SM Higgs boson signal is 1 and for the SM background is 0.

BDT for categorization For event categorization, two separate BDT classifier were developed to discriminate against ggF production: one for VBF production (BDT_{VBF}) and another for the vector boson hadronic decays of VH production (BDT_{VH}). In the first case the BDT output is used as an observable together with $m_{4\ell}$ in a maximum likelihood fit for the VBF category, while in the latter case the BDT output value is used as a selection requirement for the event to be classified in the VH-hadronic enriched category, as discussed in Sec. 7.2. In both cases the same five discriminating variables are used. In order of decreasing separation power between the two production modes, the variables are (a) invariant mass of the dijet system, (b) pseudorapidity separation between the two jets ($|\Delta\eta_{jj}|$), (c) transverse momentum of each jet, and (d) pseudorapidity of the leading jet.

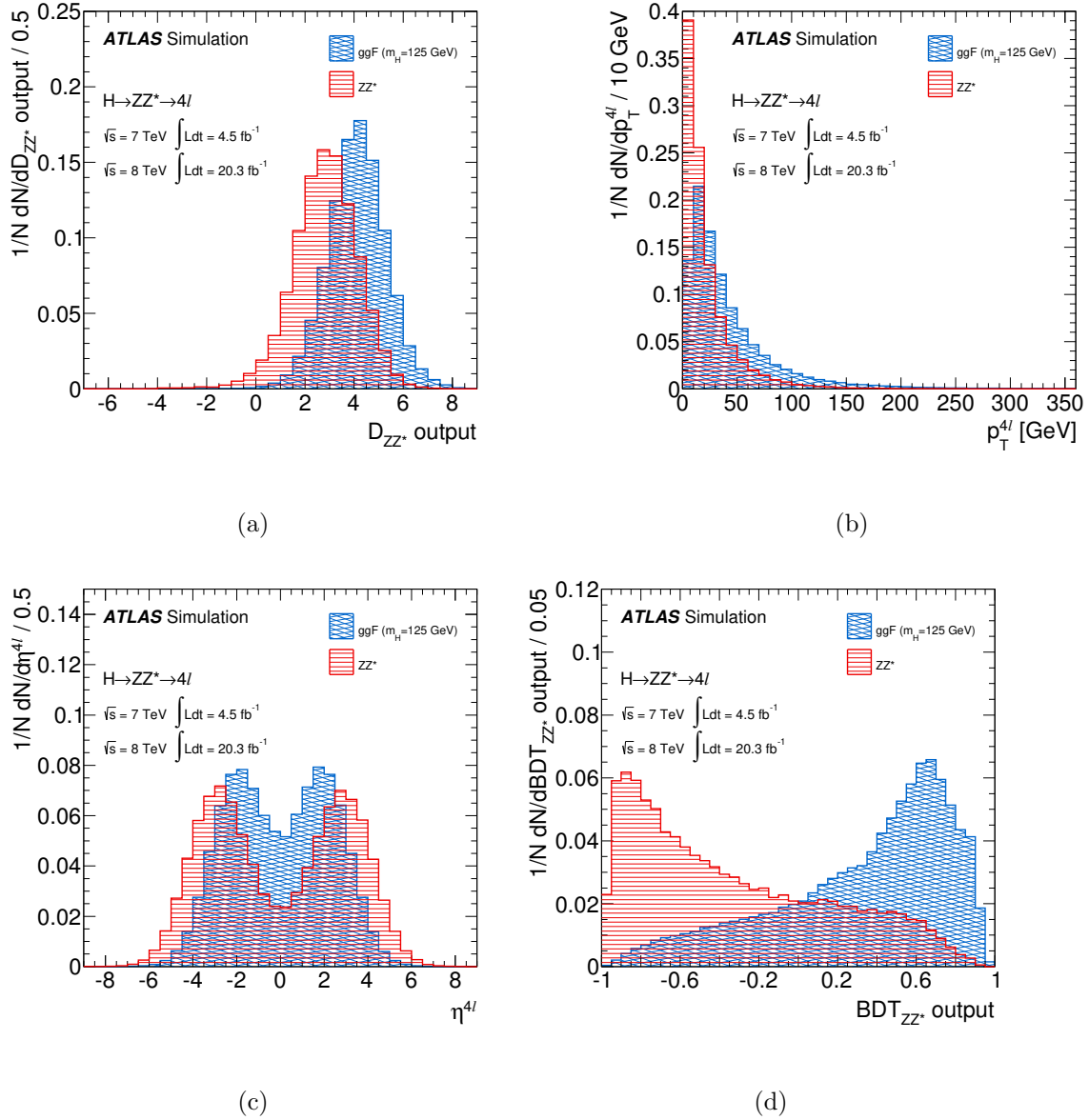


Figure 7.2: Distributions for signal (blue) and $ZZ^{(*)}$ background (red) events, showing (a) $D_{ZZ^{(*)}}$ output, (b) $p_T^{4\ell}$ and (c) $\eta^{4\ell}$ after the inclusive analysis selection in the mass range $115 < m_{4\ell} < 130 \, \text{GeV}$ used for the training of the $BDT_{ZZ^{(*)}}$ classifier. (d) output distribution for signal (blue) and $ZZ^{(*)}$ background (red) in the mass range of $115 < m_{4\ell} < 130 \, \text{GeV}$. All histograms are normalized to the same area.

For the training of the BDT discriminant, fully simulated four-lepton Higgs boson signal events produced through ggF and VBF production and hadronically decaying vector boson events for VH production are used. The distributions of these variables for BDT_{VBF} are presented in Figs. 7.3(a)– 7.3(e), where all the expected features of the VBF production of a Higgs boson can be seen: the dijet system has a high invariant mass and the two jets are emitted in opposite high- $|\eta|$ regions with a considerable $\Delta\eta$ separation between them. The jets from ggF production, on the other hand, are more centrally produced and have a smaller invariant mass and $\Delta\eta$ separation. The separation between VBF and ggF can be seen in the output of BDT_{VBF} in Fig 7.3(f), where the separation between VBF and $\text{ZZ}^{(*)}$ is found to be similar. The output of BDT_{VBF} is unchanged for various mass points around the main training mass of $m_H = 125 \text{ GeV}$. For variables entering the BDT_{VH} discriminant, the invariant mass of the dijet system, which peaks at the Z mass, exhibits the most important difference between ggF and VH production modes. The other variables have less separation power. The corresponding separation for BDT_{VH} is shown in Fig. 7.4. As described in Sec. 7.2, the VH-hadronic enriched category applies a selection on the BDT_{VH} discriminant (< -0.4) which optimizes the signal significance.

7.5 Signal and background modeling

To enhance analysis sensitivities different discriminants are used in different categories. In the **ggF-enriched category**, a two-dimensional (2D) fit to $m_{4\ell}$ and the $\text{BDT}_{\text{ZZ}^{(*)}}$ output ($O_{\text{BDT}_{\text{ZZ}^{(*)}}}$) is used, because it provides the smallest expected uncertainties for the inclusive signal strength measurements and the largest expected significance over a background hypothesis. A kernel density estimation method [155]

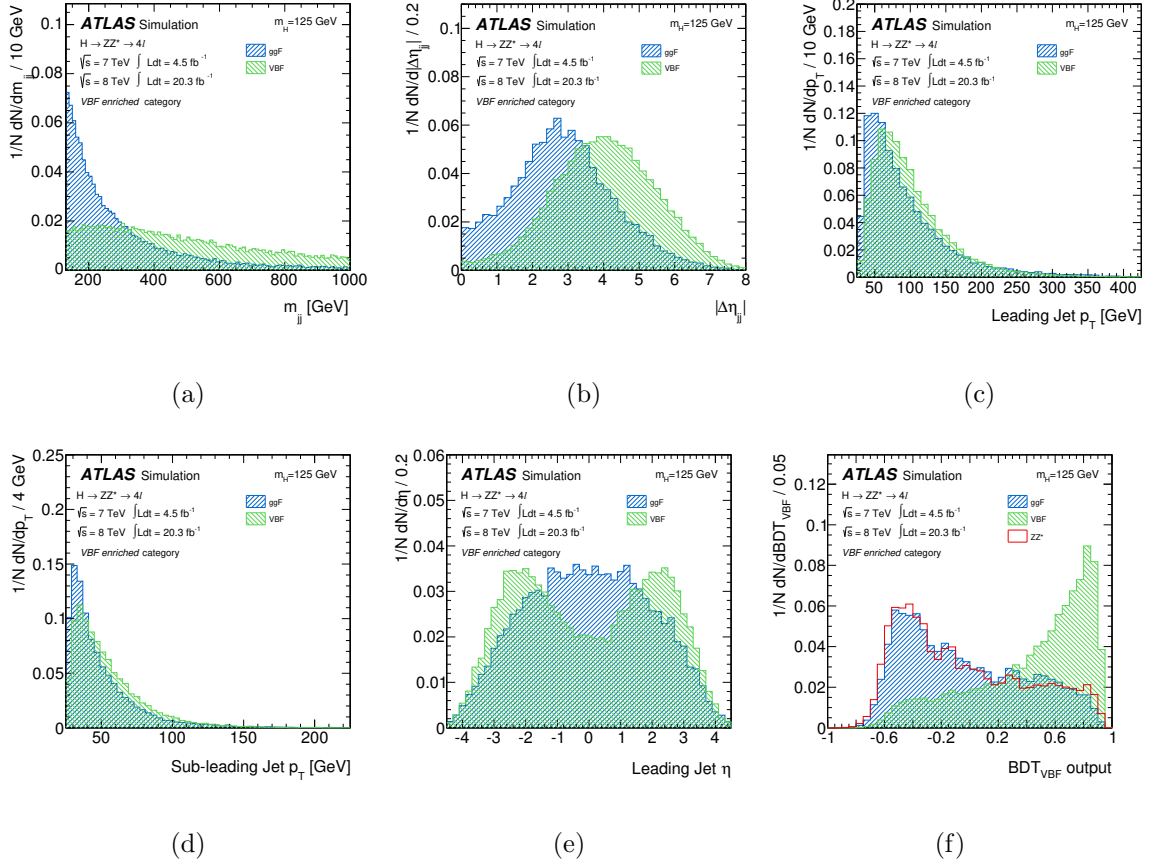


Figure 7.3: Distributions of kinematic variables for signal (VBF events, green) and background (ggF events, blue) events used in the training of the BDT_{VBF} : (a) dijet invariant mass, (b) dijet η separation, (c) leading jet p_T , (d) subleading jet p_T , (e) leading jet η , (f) output distributions of BDT_{VBF} for VBF and ggF events as well as the $ZZ^{(*)}$ background (red). All histograms are normalized to the same area.

uses fully simulated events to obtain smooth distributions for the 2D signal models. These distributions are produced using samples events at 15 different m_H values in the range 115–130 GeV and parametrised as functions of m_H using B-spline interpolation.

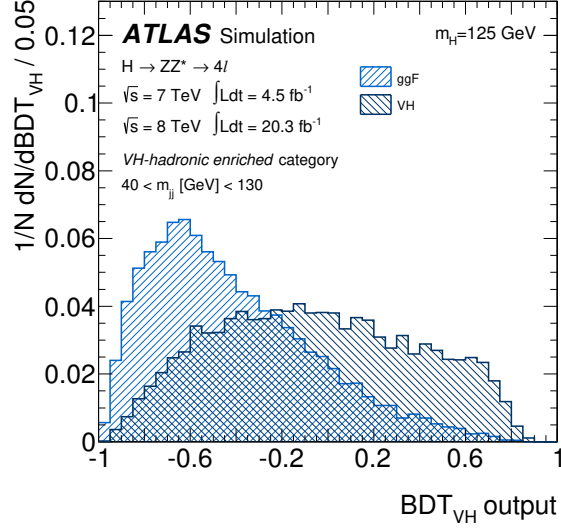


Figure 7.4: BDT_{VH} discriminant output for the VH-hadronic enriched category for signal (VH events, dark blue) and background (ggF events, blue) events.

The probability density function for the signal in the 2D fit is

$$\begin{aligned} \mathcal{P}(m_{4\ell}, O_{\text{BDT}_{\text{ZZ}^{(*)}}}|m_H) &= \mathcal{P}(m_{4\ell}|O_{\text{BDT}_{\text{ZZ}^{(*)}}}, m_H) \mathcal{P}(O_{\text{BDT}_{\text{ZZ}^{(*)}}}|m_H) \\ &\simeq \left(\sum_{n=1}^4 \mathcal{P}(m_{4\ell}|m_H) \theta_n(O_{\text{BDT}_{\text{ZZ}^{(*)}}}) \right) \mathcal{P}(O_{\text{BDT}_{\text{ZZ}^{(*)}}}|m_H) \end{aligned} \quad (7.1)$$

where θ_n defines four equal-sized bins for the value of the $\text{BDT}_{\text{ZZ}^{(*)}}$ output, and $\mathcal{P}_n$ represents the 1D probability density function of the signal in the corresponding $\text{BDT}_{\text{ZZ}^{(*)}}$ bin. The variation of the $m_{4\ell}$ shape is negligible within a signal $\text{BDT}_{\text{ZZ}^{(*)}}$ bin. The background model, $\mathcal{P}_{\text{bkg}}(m_{4\ell}, O_{\text{BDT}_{\text{ZZ}^{(*)}}})$, is described using a two-dimensional probability density. For the $\text{ZZ}^{(*)}$ and reducible $\ell\ell + \mu\mu$ backgrounds, the 2D probability density distributions are derived from simulation, where $\ell\ell + \mu\mu$ simulation was shown to agree well with data in the control region. For the $\ell\ell + ee$ background model, the two dimensional probability density can only be obtained from data, which is done using the $3\ell + X$ data control region weighted with the transfer factor to match

the kinematics of the signal region. Figure 7.5 shows the probability density in the $O_{\text{BDT}_{ZZ^{(*)}}}-m_{4\ell}$ plane, for the signal with $m_H = 125$ GeV, the $ZZ^{(*)}$ background from simulation and the reducible background from the data control region. With respect to a 1D approach, there is an expected reduction of the statistical uncertainty for the inclusive signal strength measurements, which is estimated from simulation to be approximately 8% for both measurements. Both the 1D and the 2D models are built using $m_{4\ell}$ after applying a Z-mass constraint to m_{12} during the fit, as described in Chapter 6. Figure 8.3 shows the $m_{4\ell}$ distribution for a simulated signal sample with $m_H = 125$ GeV, after applying the correction for final-state radiation and the Z-mass constraint for the 4μ , $4e$ and $2e2\mu/2\mu2e$ final states. The width of the reconstructed Higgs boson mass for $m_H = 125$ GeV ranges between 1.6 GeV (4μ final state) and 2.2 GeV ($4e$ final state) and is expected to be dominated by the experimental resolution since, for m_H of about 125 GeV, the natural width in the SM is approximately 4 MeV.

In the **VBF enriched** category, where the BDT_{VBF} discriminant is introduced to separate the ggF-like events from VBF-like events, the 2D probability density $\mathcal{P}(m_{4\ell}, O_{\text{BDT}_{\text{VBF}}})$ is constructed by factorizing the BDT_{VBF} output and $m_{4\ell}$ distributions. This factorization is justified by the negligible dependence of the BDT_{VBF} output on $m_{4\ell}$ for both signal and background. The BDT_{VBF} output dependence on the Higgs boson mass is negligible and is neglected in the probability density. Adding the BDT_{VBF} in the VBF enriched category reduces the expected uncertainty on the signal strength of the VBF and VH production mechanisms $\mu_{\text{VBF}+\text{VH}}$ by about 25%. The improvement in the expected uncertainty on $\mu_{\text{VBF}+\text{VH}}$ reaches approximately 35% after adding the leptonic and hadronic VH categories to the model.

In the **VH-hadronic and VH-leptonic enriched** categories, one dimensional fit to the $m_{4\ell}$ observable is performed, since for the VH-hadronic enriched category, a selection on the BDT_{VH} is included in the event selection.

7.6 Systematic uncertainties

The uncertainties on the lepton reconstruction and identification efficiency, and on the lepton energy or momentum resolution and scale, are determined using samples of W , Z and J/Ψ decays. The efficiency to trigger, reconstruct and identify electrons and muons are studied using $Z \rightarrow \ell\ell$ and $J/\Psi \rightarrow \ell\ell$ decays. The expected impact from simulation of the associated systematic uncertainties on the signal yield is presented in Table 7.3. The impact is presented for the individual final states and for all channels combined.

The level of agreement between data and simulation for the efficiency of the isolation and impact parameter requirements of the analysis is studied using a tag-and-probe method. As a result, a small additional uncertainty on the isolation and impact parameter selection efficiency is applied for electrons with E_T below 15 GeV. The effect of the isolation and impact parameter uncertainties on the signal strength is given in Table 7.3. The corresponding uncertainty for muons is found to be negligible.

The uncertainties on the data-driven estimates of the background yields are discussed in Chapter 6.3 and summarized in Table 7.2, and their impact on the signal strength is given in Table 7.3.

Uncertainties on the predicted Higgs boson p_T spectrum due to those on the PDFs and higher-order corrections are estimated to affect the signal strength by less than $\pm 1\%$. The systematic uncertainty of the $ZZ^{(*)}$ background rate is around $\pm 4\%$

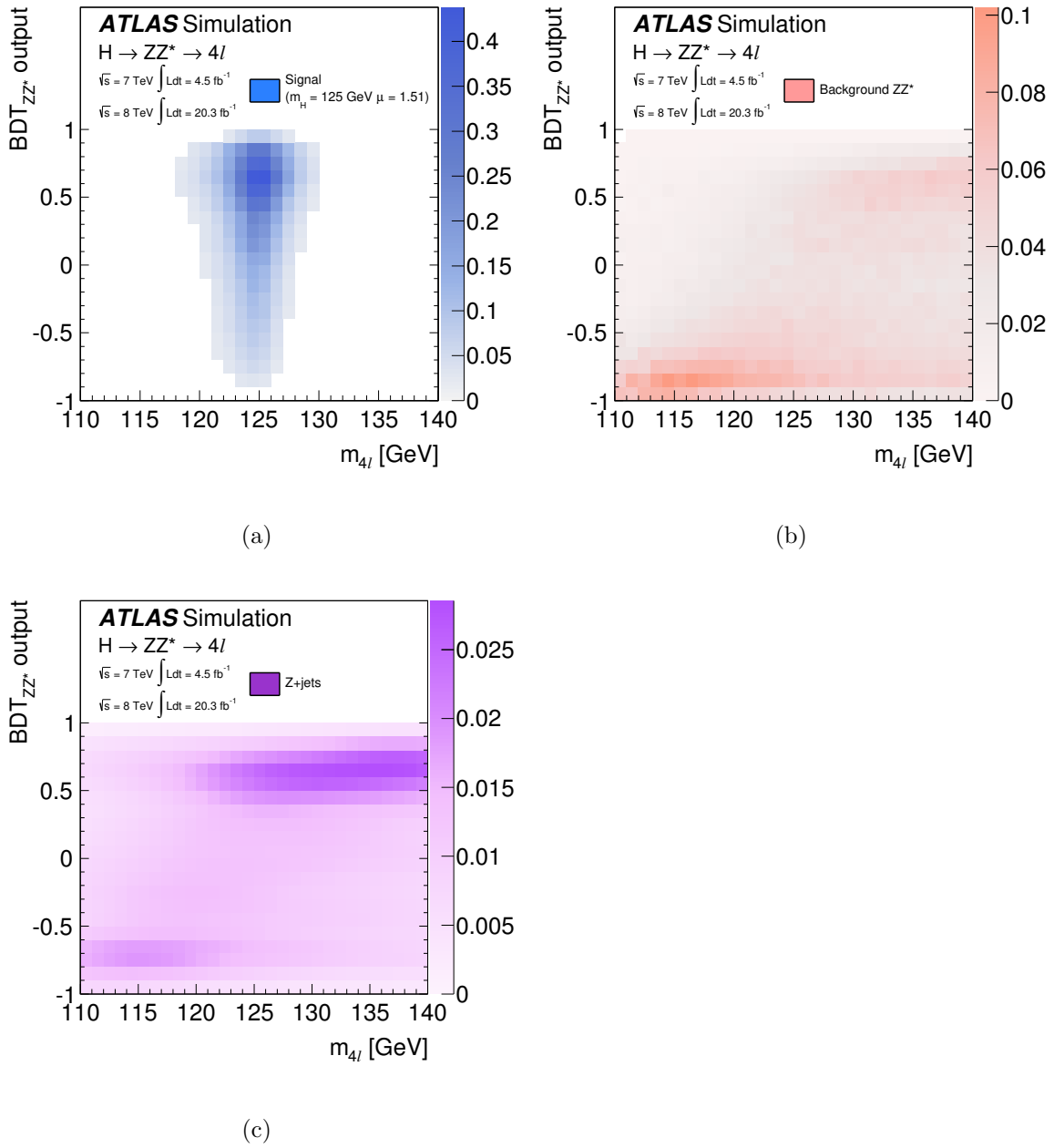


Figure 7.5: Probability density for the signal and different backgrounds normalized to the expected number of events for the 2011 and 2012 data sets, summing over all the final states: (a) $\mathcal{P}(m_{4\ell}, O_{\text{BDT}_{ZZ^{(*)}}}|m_H)$ for the signal assuming $m_H = 125 \text{ GeV}$, (b) $\mathcal{P}(m_{4\ell}, O_{\text{BDT}_{ZZ^{(*)}}})$ for the $ZZ^{(*)}$ background and (c) $\mathcal{P}(m_{4\ell}, O_{\text{BDT}_{ZZ^{(*)}}})$ for the reducible background.

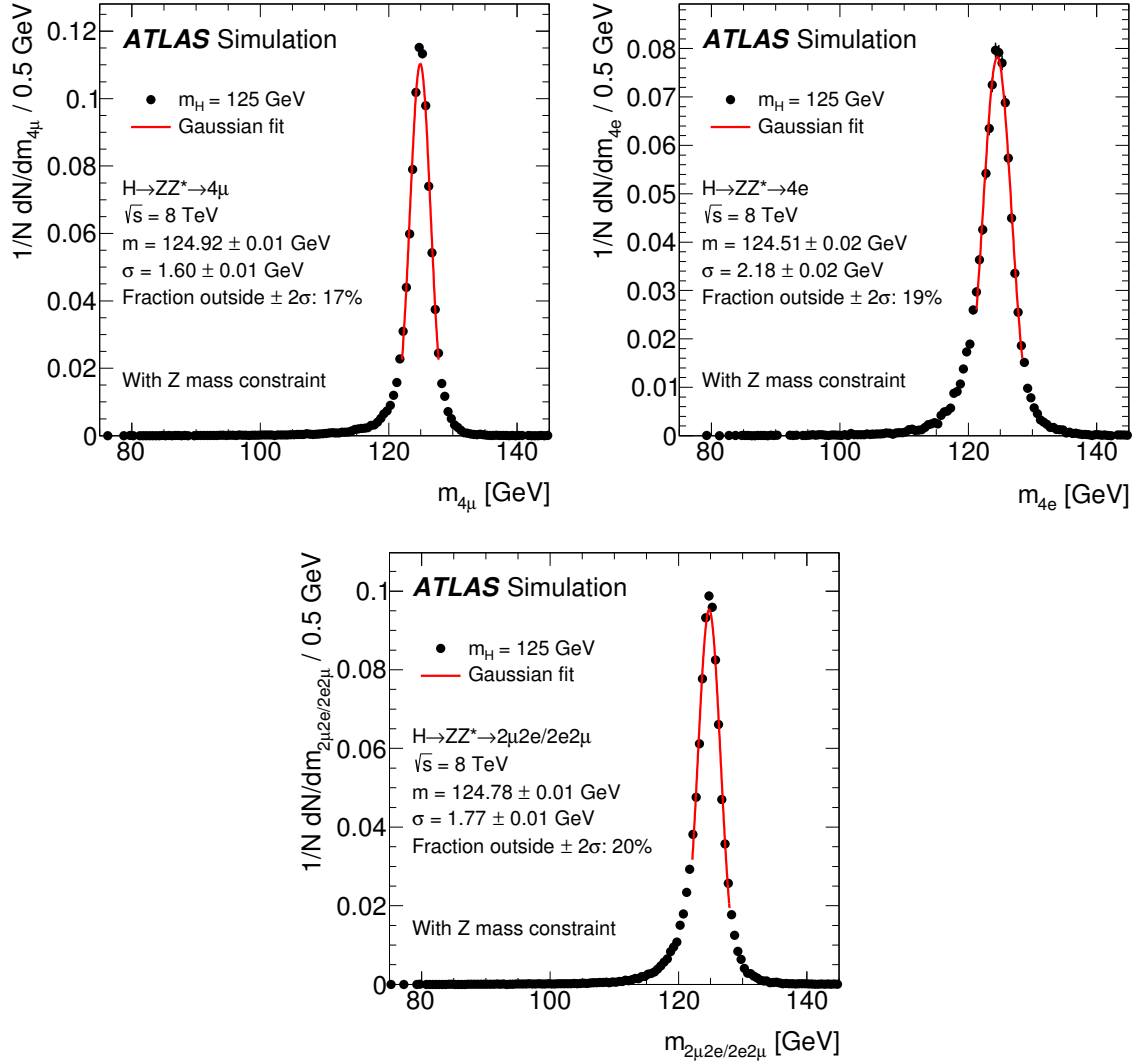


Figure 7.6: Invariant mass distribution for a simulated signal sample with $m_H = 125$ GeV, superimposed is the Gaussian fit to the $m_{4\ell}$ peak after the correction for final-state radiation and the Z-mass constraint.

for $m_{4\ell} = 125$ GeV and increases for higher mass, averaging to around $\pm 6\%$ for the $ZZ^{(*)}$ production above 110 GeV.

The main experimental uncertainty relating to categorization strategies is the jet energy scale determination, including the uncertainties associated with the modeling of the absolute and relative *in situ* jet calibrations, as well as the flavor composition of the jet sample. The impact of the jet uncertainties on the various categories is anti-correlated because a variation of the jet energy scale results primarily in the migration of events among the categories. The impact of the jet energy scale uncertainty results in an uncertainty of about $\pm 10\%$ for the VBF enriched category, $\pm 8\%$ for the VH-hadronic enriched category, $\pm 1.5\%$ for the VH-leptonic enriched category and $\pm 1.5\%$ for the ggF enriched category.

7.7 Results

The number of observed candidate events for each of the four decay channels in a mass window of 120–130 GeV and the signal and background expectations are presented in Table 7.4. Three events in the mass range $120 < m_{4\ell} < 130$ GeV are corrected for FSR: one 4μ event and one $2\mu 2e$ are corrected for non-collinear FSR, and one $2\mu 2e$ event is corrected for collinear FSR. In the full mass spectrum, there are 8 (2) events corrected for collinear (noncollinear) FSR, in good agreement with the expected number of 11 events.

The expected $m_{4\ell}$ distribution for the backgrounds and the signal hypothesis are compared with the combined 2011 and 2012 data sets in Figure 7.7. In Figure 7.7, one observes the single $Z \rightarrow 4\ell$ resonance, the threshold of the ZZ production above 180 GeV and a narrow peak around 125 GeV. The Higgs signal is shown for $m_H =$

Table 7.3: The expected impact of the systematic uncertainties on the signal yield, derived from simulation, for $m_H = 125$ GeV, are summarized for each of the four final states for the combined 2011 and 2012 data sets. The symbol “-” signifies that the systematic uncertainty does not contribute to a particular final state. The last three systematic uncertainties apply equally to all final states. All uncertainties have been symmetrized.

Source of uncertainty	4μ	$2e2\mu$	$2\mu2e$	$4e$	combined
Electron rec. and id. efficiencies	-	1.7%	3.3%	4.4%	1.6%
Electron isolation and IP selection	-	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	-	0.12%	0.05%	0.21%	< 0.2%
$\ell\ell + ee$ backgrounds	-	-	3.4%	3.4%	1.3%
Muon rec. and id. efficiencies	1.9%	1.1%	0.8%	-	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	-	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	-	-	1.2%
QCD scale uncertainty					6.5%
PDF, α_s , uncertainty					6.0%
$H \rightarrow ZZ^{(*)}$ branching ratio uncertainty					4.0%

Table 7.4: The number of events expected and observed for a $m_H = 125$ GeV hypothesis for the four-lepton final states in a window of $120 < m_{4\ell} < 130$ GeV. The second column shows the number of expected signal events for the full mass range, without a selection on $m_{4\ell}$. The other columns show for the 120–130 GeV mass range the number of expected signal events, the number of expected $ZZ^{(*)}$ and reducible background events, and the signal-to-background ratio (S/B), together with the number of observed events for 2011 and 2012 data sets as well as for the combined sample.

Final state	Signal full mass range	Signal	$ZZ^{(*)}$	Z+jets, $t\bar{t}$	S/B	Expected	Observed
$\sqrt{s} = 7$ TeV							
4μ	1.0 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.10	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
$\sqrt{s} = 8$ TeV							
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.0 ± 0.28	1.7	22.1 ± 1.5	31
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV							
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

125 GeV with a signal strength of 1.51, corresponding to the combined signal strength (μ) measurement in the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ final state, scaled to this mass by the expected variation in the SM Higgs boson cross section times branching ratio.

The local p_0 -value of the observed signal, representing the significance of the excess relative to the background-only hypothesis, is obtained with the asymptotic approximation [148] using the 2D fit without any selection on $\text{BDT}_{ZZ^{(*)}}$ output and is

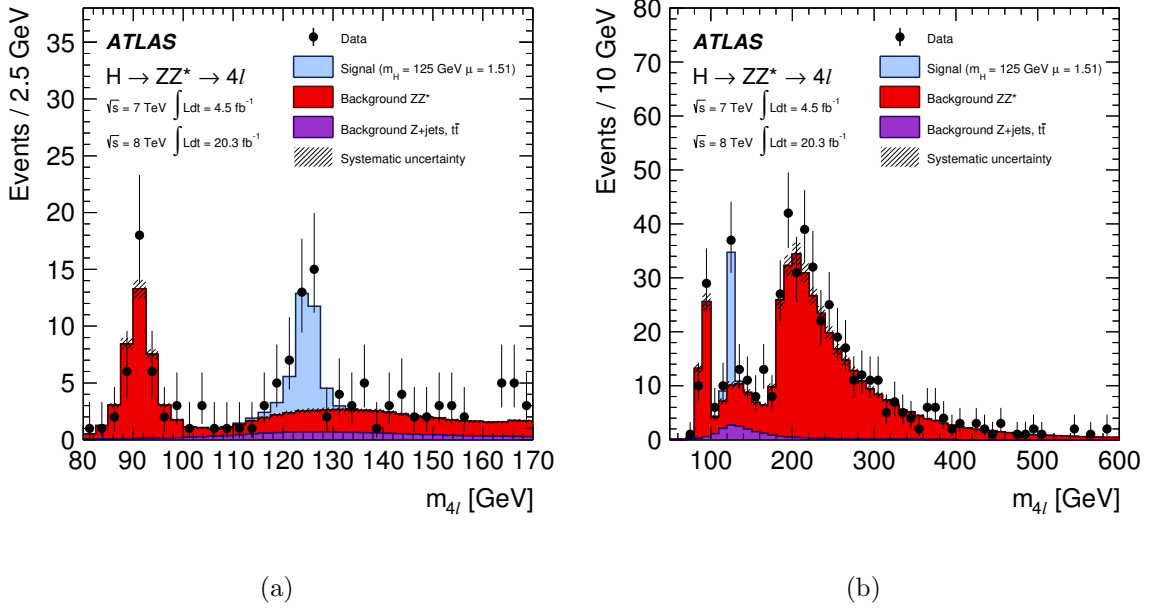


Figure 7.7: The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates (filled circles) compared to the expected signal and background contributions (filled histograms) for the combined 2011 and 2012 data sets for the mass range (a) 80–170 GeV, and (b) 80–600 GeV. The signal expectation shown is for a mass hypothesis of $m_H = 125$ GeV and normalized to $\mu = 1.51$ (see text). The expected backgrounds are shown separately for the $ZZ^{(*)}$ (red histogram), and the reducible Z+jets and $t\bar{t}$ backgrounds (violet histogram); the systematic uncertainty associated to the total background contribution is represented by the hatched areas.

shown as a function of m_H in Figure 7.8. The local significance of the excess observed at the measured mass for this channel, 124.51 GeV, is 8.2 standard deviations. At the value of the Higgs boson mass, $m_H = 125.36$ GeV, obtained from the combination of the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ and $H \rightarrow \gamma\gamma$ mass measurement [152], the local significance decreases to 8.1 standard deviations. The expected significance at these two masses is 5.8 and 6.2 standard deviations, respectively.

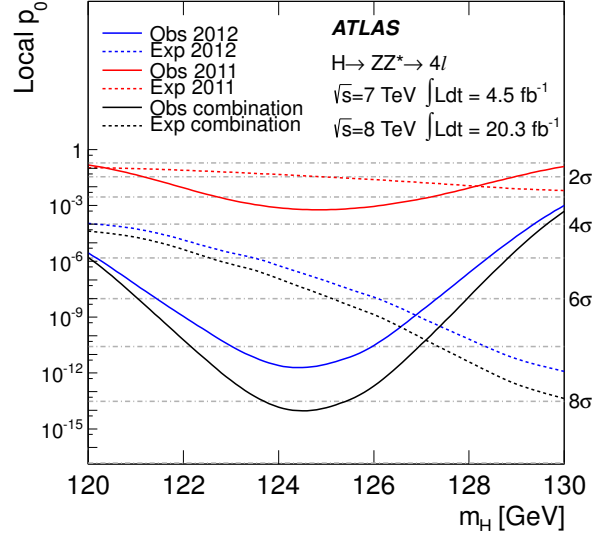


Figure 7.8: The observed local p_0 -value for the combination of the 2011 and 2012 data sets (solid black line) as a function of m_H ; the individual results for $\sqrt{s} = 7$ TeV and 8 TeV are shown separately as red and blue solid lines, respectively. The dashed curves show the expected median of the local p_0 -value for the signal hypothesis with a signal strength $\mu = 1$, when evaluated at the corresponding m_H . The horizontal dot-dashed lines indicate the p_0 -values corresponding to local significances of 1–8 σ .

The measured Higgs boson mass obtained with the 2D method is $m_H = 124.51 \pm 0.52$ GeV. The signal strength at this value of m_H is $\mu = 1.66^{+0.398}_{-0.34}(\text{stat})^{+0.21}_{-0.14}(\text{syst})$. The production mechanisms are grouped into the “fermionic” and the “bosonic” ones. The former consists of ggF , $b\bar{b}H$ and $t\bar{t}H$, while the latter includes the VBF and VH modes. The measured value for $\mu_{ggF+b\bar{b}H+t\bar{t}H}$ is: $1.66^{+0.45}_{-0.41}(\text{stat})^{+0.25}_{-0.15}(\text{syst})$; and the measured value for $\mu_{\text{VBF}+\text{VH}}$ is: $0.26^{+1.60}_{-0.91}(\text{stat})^{+0.36}_{-0.23}(\text{syst})$.

Chapter 8

Search for additional heavy scalars in the $\ell^+\ell^-\ell^+\ell^-$ final states and combination with results from $\ell^+\ell^-\nu\bar{\nu}$ final states

8.1 Overview

The observation of the SM Higgs boson does not exclude the possibility that it may be a part of an extended Higgs sector, as predicted by several beyond the SM models [67, 156]. The search for additional heavy scalars in the $\ell^+\ell^-\ell^+\ell^-$ final state uses an integrated luminosity of 36.1 fb^{-1} pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected by ATLAS during 2015 and 2016 to look for a peak structure on top of a continuous background spectrum in the four-lepton invariant mass distribution. The signal and background modeling is described in Section 8.2, followed by the evaluation of systematic uncertainties in Section 8.3. The results in the $\ell^+\ell^-\ell^+\ell^-$ final state are presented in Section 8.4. In order to improve the sensitivity of searching for a heavy scalar in the high mass range, results from the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states are

combined. Section 8.5 briefly introduces the $\ell^+\ell^-\nu\bar{\nu}$ analysis. The relationship of the systematic uncertainties in the two analyses is important for the combination. The correlation schemes used to properly correlate the systematic uncertainties in the two analyses are discussed in Section 8.5.2, followed by the impact of the systematic uncertainties on the signal cross section in Section 8.5.3. The combined results are then presented in Section 8.5.4.

8.2 Signal and background modeling

The parameterisation of the reconstructed four-lepton invariant mass $m_{4\ell}$ distribution for signal and background is based on the MC simulation and used to fit the data.

In the case of a narrow resonance, the width in $m_{4\ell}$ is determined by the detector resolution, which is modelled by the sum of a Crystal Ball ($\mathcal{C}$) function [157,158] and a Gaussian ($\mathcal{G}$) function:

$$P_s(m_{4\ell}) = f_{\mathcal{C}} \times \mathcal{C}(m_{4\ell}; \mu, \sigma_{\mathcal{C}}, \alpha_{\mathcal{C}}, n_{\mathcal{C}}) + (1 - f_{\mathcal{C}}) \times \mathcal{G}(m_{4\ell}; \mu, \sigma_{\mathcal{G}}).$$

The Crystal Ball and the Gaussian functions share the same peak value of $m_{4\ell}$ (μ), but have different resolution parameters, $\sigma_{\mathcal{C}}$ and $\sigma_{\mathcal{G}}$. The $\alpha_{\mathcal{C}}$ and $n_{\mathcal{C}}$ parameters control the shape and position of the non-Gaussian tail, and the parameter $f_{\mathcal{C}}$ ensures the relative normalization of the two probability density functions. To improve the stability of the parameterization in the full mass range considered, the parameter $n_{\mathcal{C}}$ is set to a fixed value. The bias in the extraction of signal yields introduced by using the analytical function is below 1.5%. The function parameters are determined separately for each final state using signal simulation, and fitted to first- and second-degree polynomials

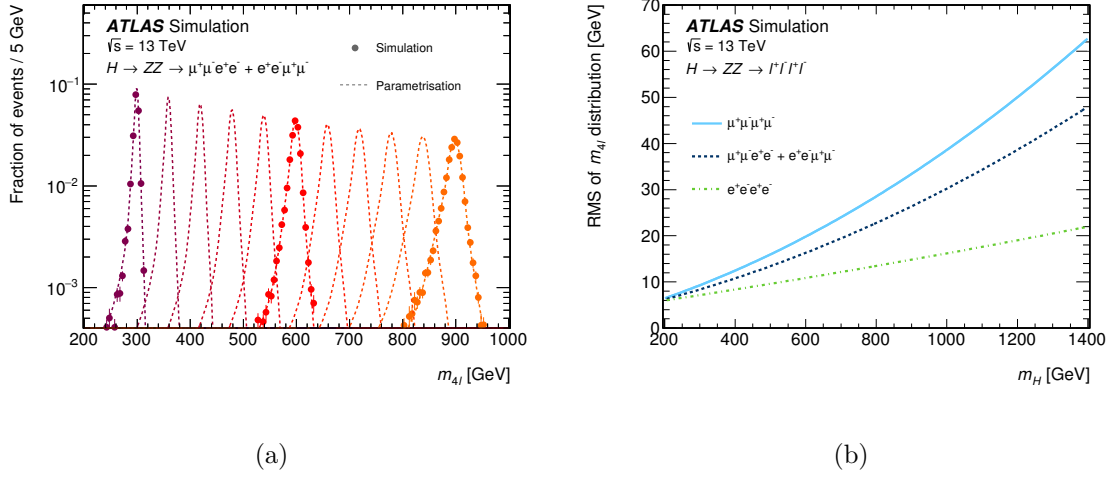


Figure 8.1: (a) Parameterisation of the four-lepton invariant mass ($m_{4\ell}$) spectrum for various resonance mass (m_H) hypotheses in the NWA. Markers show the simulated $m_{4\ell}$ distribution for three specific values of m_H (300, 600, 900 GeV), normalized to unit area, and the dashed lines show the parameterization used in the $2e2\mu$ channel for these mass points as well as for intervening ones. (b) RMS of the four-lepton invariant mass distribution as a function of m_H .

in scalar mass m_H to interpolate between the generated mass points. The use of this parameterization for the function parameters introduces an extra bias in the signal yield and m_H extraction of about 1%. An example of this parameterization is illustrated in Figure 8.1, where the left plot shows the mass distribution for simulated samples at $m_H = 300, 600, 900$ GeV and the right plot shows the root mean square (RMS) of the $m_{4\ell}$ distribution in the range considered for this search.

In the case of the LWA, the particle-level line-shape of $m_{4\ell}$ is derived from a theoretical calculation, as described in Ref. [159], and is then convolved with the detector resolution, using the same procedure as for the modeling of the narrow resonance.

The $m_{4\ell}$ distribution for the ZZ continuum background is taken from MC sim-

ulation, and parameterized by an empirical function for both the quark- and gluon-initiated processes:

$$f_{qqZZ/ggZZ}(m_{4\ell}) = (f_1(m_{4\ell}) + f_2(m_{4\ell})) \times H(m_0 - m_{4\ell}) \times C_0 + f_3(m_{4\ell}) \times H(m_{4\ell} - m_0),$$

where:

$$\begin{aligned} f_1(m_{4\ell}) &= \exp(a_1 + a_2 \cdot m_{4\ell}), \\ f_2(m_{4\ell}) &= \left\{ \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left(\frac{m_{4\ell} - b_1}{b_2} \right) \right\} \times \frac{1}{1 + \exp \left(\frac{m_{4\ell} - b_1}{b_3} \right)}, \\ f_3(m_{4\ell}) &= \exp \left(c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^{2.7} \right), \\ C_0 &= \frac{f_3(m_0)}{f_1(m_0) + f_2(m_0)}. \end{aligned}$$

The function's first part, f_1 , covers the low-mass part of the spectrum where one of the Z bosons is off-shell, while f_2 models the ZZ threshold around $2 \cdot m_Z$ and f_3 describes the high-mass tail. The transition between low- and high-mass parts is performed by the Heaviside step function $H(x)$ around $m_0 = 240$ GeV. The continuity of the function around m_0 is ensured by the normalization factor C_0 that is applied to the low-mass part. Finally, a_i , b_i and c_i are shape parameters which are obtained by fitting the $m_{4\ell}$ distribution in simulation for each category. The uncertainties in the values of these parameters from the fit are found to be negligible. The MC statistical uncertainties in the high-mass tail are taken into account by assigning a 1% uncertainty to c_4 .

The $m_{4\ell}$ shapes are extracted from simulation for most background components ($t\bar{t}V$, VVV , $\ell\ell + \mu\mu$ and heavy-flavour hadron component of $\ell\ell + ee$), except for the light-flavour jets and photon conversions in the case of $\ell\ell + ee$ background, which is taken from the control region as described in Section 6.3.3.

Interference modeling The gluon-initiated production of a heavy scalar H , the SM h and the $gg \rightarrow ZZ^{(*)}$ continuum background all share the same initial and final state, and thus lead to interference terms in the total amplitude. Theoretical calculations described in Ref. [160] have shown that the effect of interference could modify the integrated cross section by up to $\mathcal{O}(10\%)$, and this effect is enhanced as the width of the heavy scalar increases. Therefore, a search for a heavy scalar Higgs boson in the LWA case must properly account for two interference effects: the interference between the heavy scalar and the SM Higgs boson (denoted by H – h) and between the heavy scalar and the $gg \rightarrow ZZ^{(*)}$ continuum (denoted by H – B).

Assuming that H and h bosons have similar properties, they have the same production and decay amplitudes structure and therefore the only difference between the signal and interference terms in the production cross section comes from the propagator. Hence, the acceptance and resolution of the signal and interference terms are expected to be the same. The H – h interference is obtained by reweighting the particle-level line-shape of generated signal events using the following formula:

$$w(m_{4\ell}) = \frac{2 \cdot \text{Re} \left[\frac{1}{s-s_H} \cdot \frac{1}{(s-s_h)^*} \right]}{\frac{1}{|s-s_H|^2}},$$

where $1/(s - s_{H(h)})$ is the propagator for a scalar (H or h). The particle-level line-shape is then convolved with the detector resolution function, and the signal and interference acceptances are assumed to be the same.

In order to extract the H – B interference contribution, signal-only and background-only samples are subtracted from the generated SBI samples. The extracted particle-level $m_{4\ell}$ distribution for the H – B interference term is then convolved with the detector

resolution.

Figure 8.2 shows the overlay of the signal, both interference effects and the total line-shape for different mass and width hypotheses assuming the couplings expected in the SM for a heavy Higgs boson. As can be seen, the two interference effects tend to cancel out, and the total interference yield is for the most part positive, enhancing the signal.

8.3 Systematic Uncertainties

The systematic uncertainties are classified into experimental and theoretical uncertainties. The first category relates to the reconstruction and identification of the physics objects (leptons and jets), their energy scale and resolution, and the integrated luminosity. Systematic uncertainties on the data-driven background estimates are also included in this category. The second category includes uncertainties on the theoretical description of the signal and background processes.

In both cases the uncertainties are implemented as additional nuisance parameters (NP) that are constrained by a Gaussian distribution in the profiled likelihood. The uncertainties affect the signal acceptance, its selection efficiency and the discriminant distributions as well as the background estimates. Each source of uncertainties is either fully correlated or anti-correlated among different categories.

Experimental uncertainties The uncertainty on the combined 2015 and 2016 integrated luminosity is 4.5%. This is derived from a preliminary calibration of the luminosity scale using x - y beam separation scans performed in May 2016, following a methodology similar to that detailed in Ref [82].

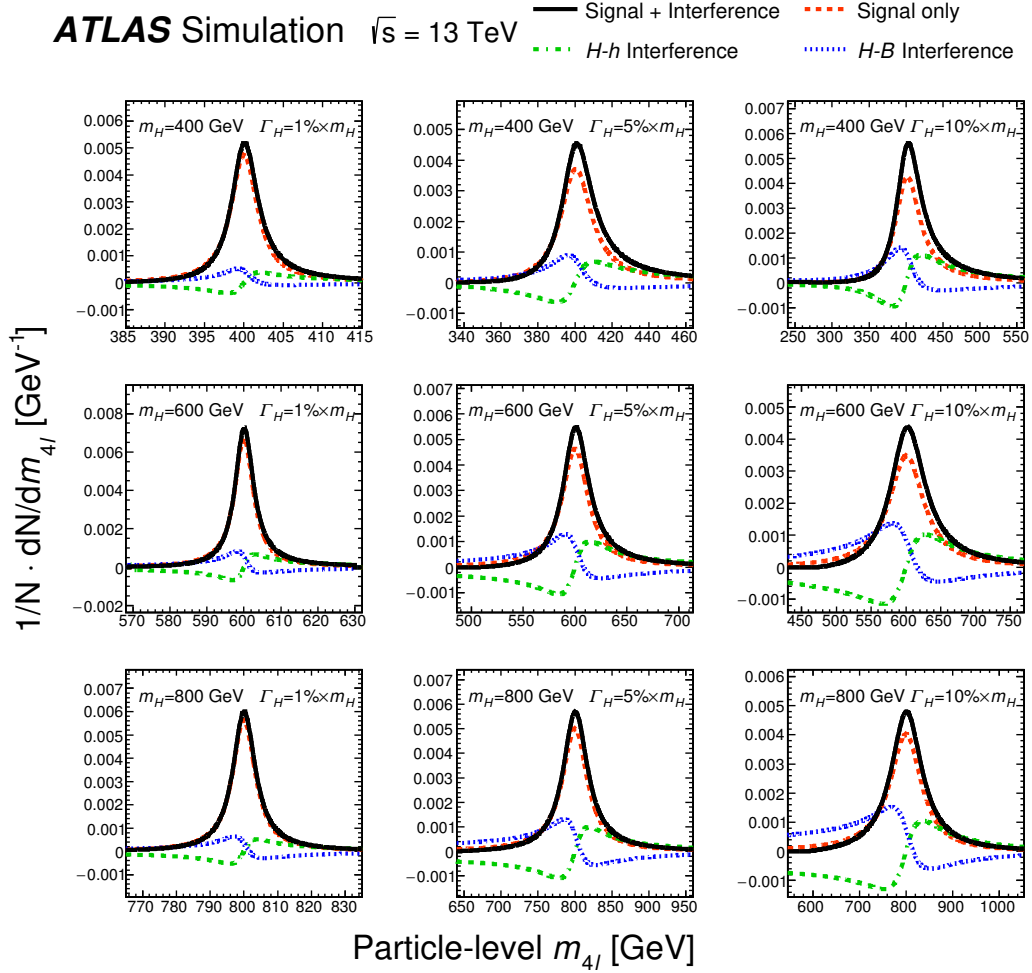


Figure 8.2: Particle-level four-lepton mass $m_{4\ell}$ model for signal only (red), H - h interference (green), H - B interference (blue) and the sum of the three processes (black). Three values of the resonance mass m_H (400, 600, 800 GeV) are chosen, as well as three values of the resonance width Γ_H (1%, 5%, 10% of m_H). The signal cross section, which determines the relative contribution of the signal and interference, is taken to be the cross section of the expected limit for each combination of m_H and Γ_H . The full model (black) is finally normalised to unity and the other contributions are scaled accordingly.

The efficiency of electron selections are broken down to different sources: trigger, identification, reconstruction and isolation, and derived from data with large statistics of the $J/\psi \rightarrow \ell\ell$ and $Z \rightarrow \ell\ell$ events. The uncertainties on the reconstruction performance are computed by following the method described in Ref [161] for the muons and Ref [162] for the electrons. Typical uncertainties on the identification efficiencies ranges from 0.5% to 1.0% for muons and 1.0% to 1.3% for electrons. The uncertainties on the electron energy scale, muon momentum and their resolutions are small.

The uncertainties on the jet energy scale and resolution have several sources, including uncertainties on the absolute and relative *in situ* calibration, the correction for pile-up, the flavor composition and response. These uncertainties are separated into independent components, and vary from 6% for jets with transverse momentum $p_T = 20$ GeV, decreasing to 1% for jets with $p_T = 200 - 1800$ GeV and increasing again to 3% for jets with higher p_T , for the average pile-up conditions of 2015 and 2016 data taking period.

The efficiencies for the lepton triggers in events with reconstructed leptons are nearly 100%, and hence the related uncertainties are negligible.

Theoretical uncertainties For simulated signal and backgrounds, theoretical modeling uncertainties associated with PDF, missing QCD higher order corrections (via variations of factorization and renormalization scales), and parton showering uncertainties are considered.

For various signal hypothesis, the dominant theoretical modeling uncertainties are due to the missing QCD higher order corrections and to the parton showering. The missing QCD higher order corrections for the events from the ggF production that fall

into the VBF-enriched category are evaluated using MADGRAPH5_aMC@NLO and affect the signal acceptance by 10%. Parton showering uncertainties are of order 10% and are evaluated by comparing PYTHIA 8.2 to the HERWIG7 [163] generator.

For the $q\bar{q} \rightarrow ZZ^{(*)}$ background, the effect of the PDF uncertainties in the full mass range varies between 2% and 5% in all categories, and that of missing QCD higher order corrections is about 10% in the ggF-enriched categories and 30% in the VBF-enriched category. The parton showering uncertainties result in less than 1% impact in the ggF-enriched categories and about 10% impact in the VBF-enriched category.

For the $gg \rightarrow ZZ^{(*)}$ background, as described in Chapter 4, a 60% relative uncertainty on the inclusive cross section is considered, while a 100% uncertainty is assigned in the VBF-enriched category.

8.4 Results and Statistical interpretation

8.4.1 Observed events in signal region

The expected number of events from each SM background within each category, as well as the observed number of events, are recorded in Table 8.1. The yield in the mass range $m_{4\ell} > 130$ GeV is 1189 events observed in data compared to 1030.5 ± 127.8 (including statistical and systematic uncertainty) events for the expected backgrounds. This corresponds to a 1.2σ global excess in data. The excess in the VBF-like category is with a global significance of about 1.3σ .

Table 8.1: Number of expected and observed events for $m_{4\ell} > 130$ GeV, together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

Process	4μ channel	ggF-enriched categories $2e2\mu$ channel	$4e$ channel	VBF-enriched category
ZZ	$297 \pm 1 \pm 40$	$480 \pm 1 \pm 60$	$193 \pm 1 \pm 25$	$15 \pm 0.1 \pm 6.0$
ZZ (EW)	$1.92 \pm 0.11 \pm 0.19$	$3.36 \pm 0.14 \pm 0.33$	$1.88 \pm 0.12 \pm 0.20$	$3.0 \pm 0.1 \pm 2.2$
$Z + \text{jets}/t\bar{t}/WZ$	$3.7 \pm 0.1 \pm 0.8$	$7.8 \pm 0.1 \pm 1.1$	$4.4 \pm 0.1 \pm 0.8$	$0.37 \pm 0.01 \pm 0.05$
Other backgrounds	$5.1 \pm 0.1 \pm 0.6$	$8.7 \pm 0.1 \pm 1.0$	$4.0 \pm 0.1 \pm 0.5$	$0.80 \pm 0.02 \pm 0.30$
Total background	$308 \pm 1 \pm 40$	$500 \pm 1 \pm 60$	$203 \pm 1 \pm 25$	$19.5 \pm 0.2 \pm 8.0$
Observed	357	545	256	31

Figure 8.3 shows the four-lepton invariant mass ($m_{4\ell}$) distribution of the selected candidates compared to the background expectation in the VBF-enriched and combined ggF-enriched categories. The $m_{4\ell}$ distribution in ggF-enriched category are then separated into $4e$, $2\mu 2e$ and 4μ channels, as shown in Figure 8.4. No events are observed beyond the plotted range (to 1200 GeV). The excess at around 240 GeV is observed mostly in the $4e$ channel, while the one at 700 GeV is observed in all channels

and categories. In the $m_{4\ell}$ range [240, 245] GeV, the yield is 45 events observed in data compared to 28.3 ± 6.3 events for the expected backgrounds; while in the $m_{4\ell}$ range [650, 750] GeV, the yield is 16 events observed in data compared to 6.6 ± 2.7 events for the expected backgrounds. The significance of the two excesses evaluated from maximum likelihood is presented in Section 8.4.2.

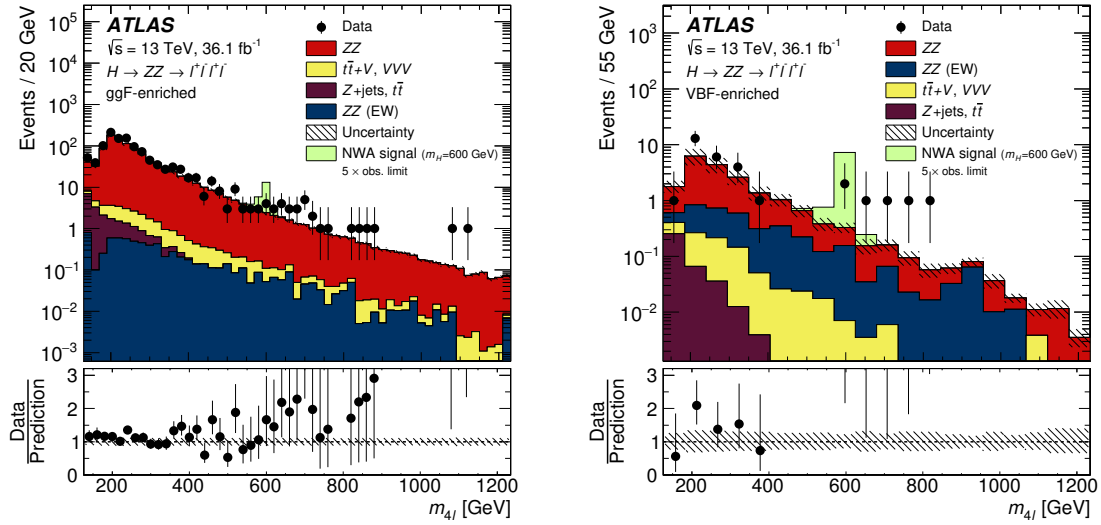


Figure 8.3: Distribution of the four-lepton invariant mass $m_{4\ell}$ in the $\ell^+\ell^-\ell^+\ell^-$ final state for (a) the ggF-enriched category (b) the VBF-enriched category. The last bin includes the overflow. The simulated $m_H = 600$ GeV signal is normalized to a cross section corresponding to five times the observed limit given in Section 8.5.4. The error bars on the data points indicate the statistical uncertainty, while the systematic uncertainty in the prediction is shown by the hatched band. The lower panels show the ratio of data to the prediction.

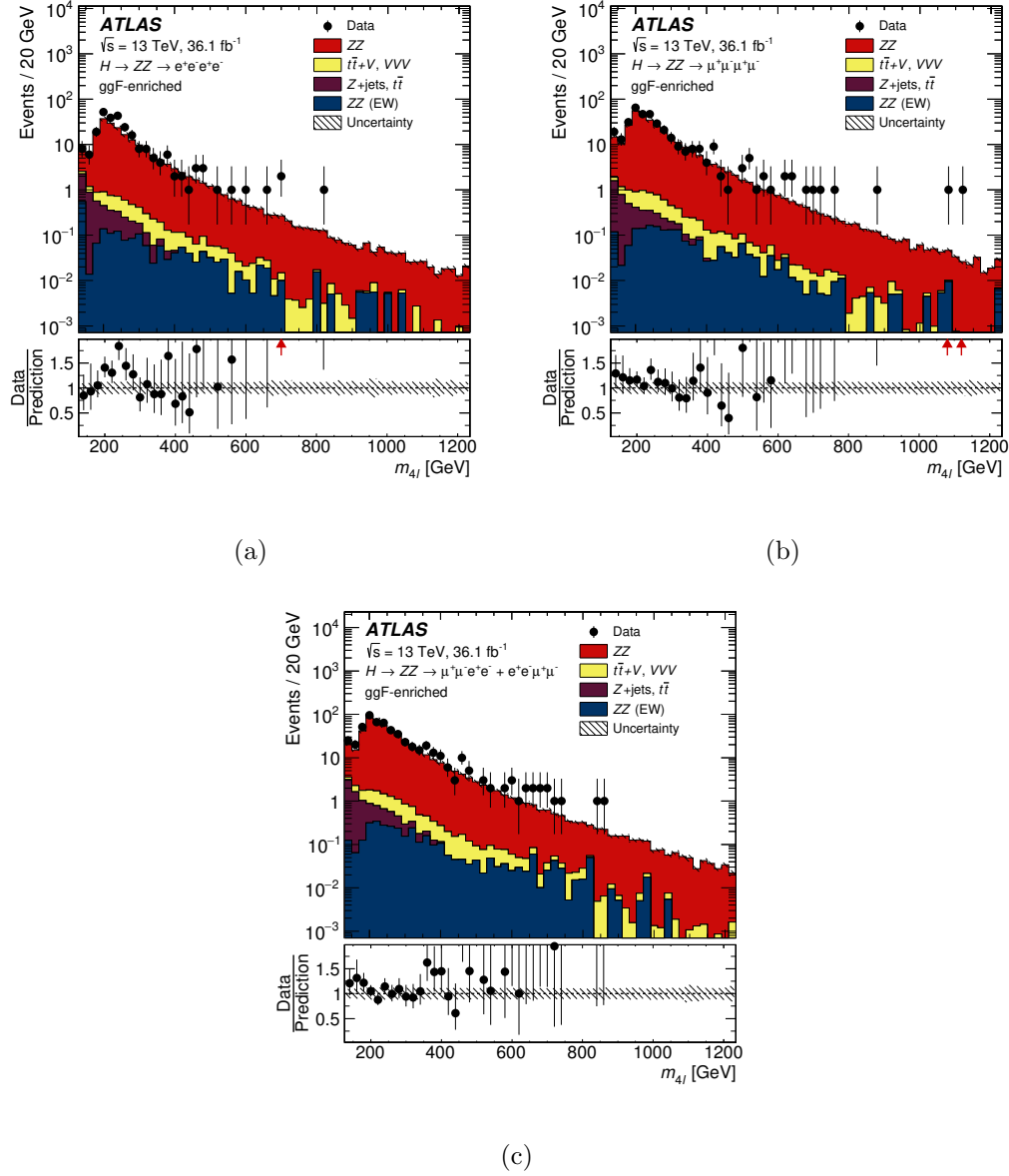


Figure 8.4: Distribution of the four-lepton invariant mass $m_{4\ell}$ in the $\ell^+\ell^-\ell^+\ell^-$ final state for (a) the ggF-like $4e$ category, (b) ggF-like 4μ category and (c) ggF-like $2\mu 2e$ categories category. The error bars on the data points indicate the statistical uncertainty, while the systematic uncertainty in the prediction is shown by the hatched band. The lower panels show the ratio of data to the prediction.

8.4.2 p_0

Figure 8.5 shows the local p_0 as a function of m_H for a scalar from gluon-fusion production under the NWA. Two excesses are observed for $m_{4\ell}$ around 240 and 700 GeV, each with a local significance of 3.6σ estimated under the asymptotic approximation, assuming the signal comes only from the ggF production. The local p_0 has non-trivial dependence on the signal hypothesis. It is checked that in the case of signal models with the LWA, the local significance is lower than the one under the NWA, indicating the two excesses are with narrow widths. The global significance, taking into account the *look-elsewhere-else* effect, is evaluated from pseudo-data in the range of $200 \text{ GeV} < m_H < 1200 \text{ GeV}$ assuming the signal comes only from the ggF production. Each pseudo-data is generated from the background-only model by randomizing the global observables and the expected yields, and then it is performed in the same way as for data to find the largest local significance for each pseudo-data. Figure 8.6 shows the distribution of the maximum local significance of each pseudo-experiment. Therefore given the search region it is expected to have a local excess with a significance of about 2.4σ . Finally, the global significance of observing an excess with a local significance of 3.6σ in the whole searching region is 2.2σ .

8.4.3 Upper limits

Narrow Width Approximation Limits on the ggF and VBF cross-sections times branching ratio assuming the Narrow Width Approximation are obtained as a function of m_H with the CL_s procedure in the asymptotic approximation. Figure 8.7 presents the expected and observed limits, at 95% confidence level, on the cross section time branching ratio of the heavy Higgs decaying to $\ell^+\ell^-\ell^+\ell^-$ final state in steps of com-

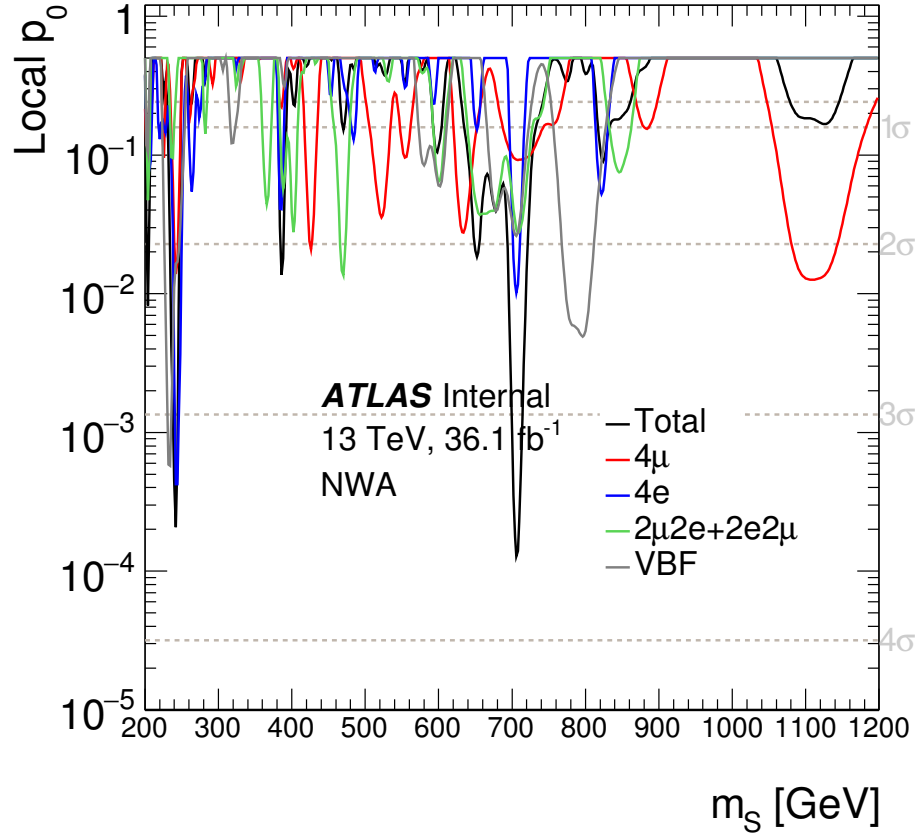


Figure 8.5: Local p_0 derived for a narrow resonance and assuming the signal comes only from the ggF production, as a function of the resonance mass m_H , using the exclusive ggF-like categories, VBF-like categories and the combined categories. Also shown are local (dot-dashed line) significance levels.

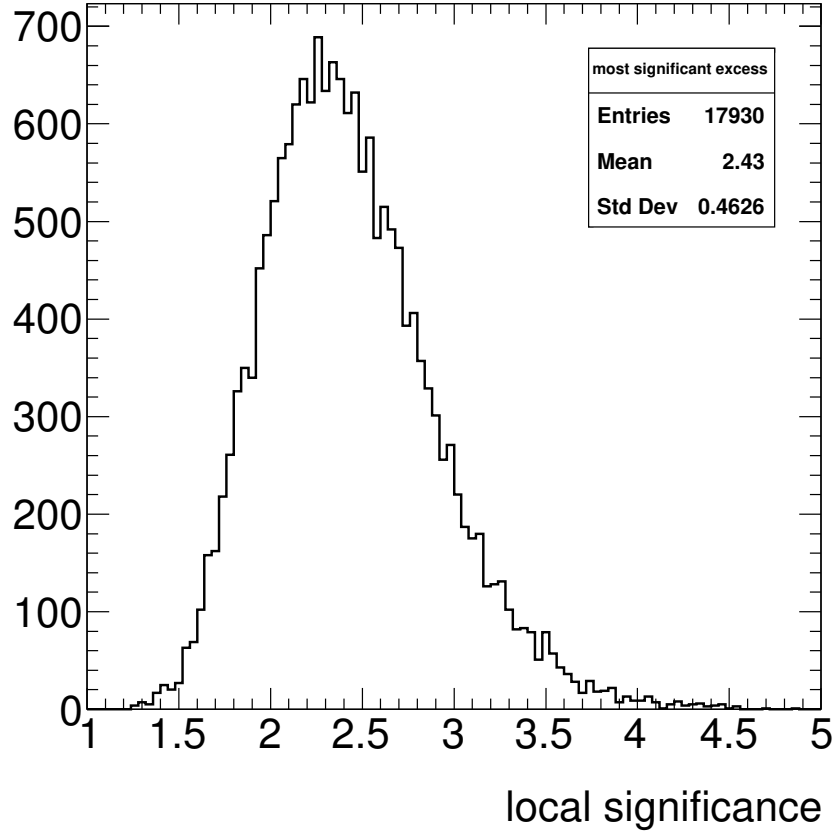


Figure 8.6: Probability distribution function of the maximum local significance in the full search range $200 < m_{4\ell} < 1200$ GeV, resulting from each of generated background-only pseudo-experiments. The mean value stands for the expected local significance resulting from background fluctuation in the full search range.

parable to the detector resolution. Without a specific model, the ratio of the ggF cross section to the VBF cross section is unknown, therefore, when setting limits on the ggF production the VBF cross section is profiled, and vice versa. This result is valid for models in which the width is less than 0.5% of m_H .

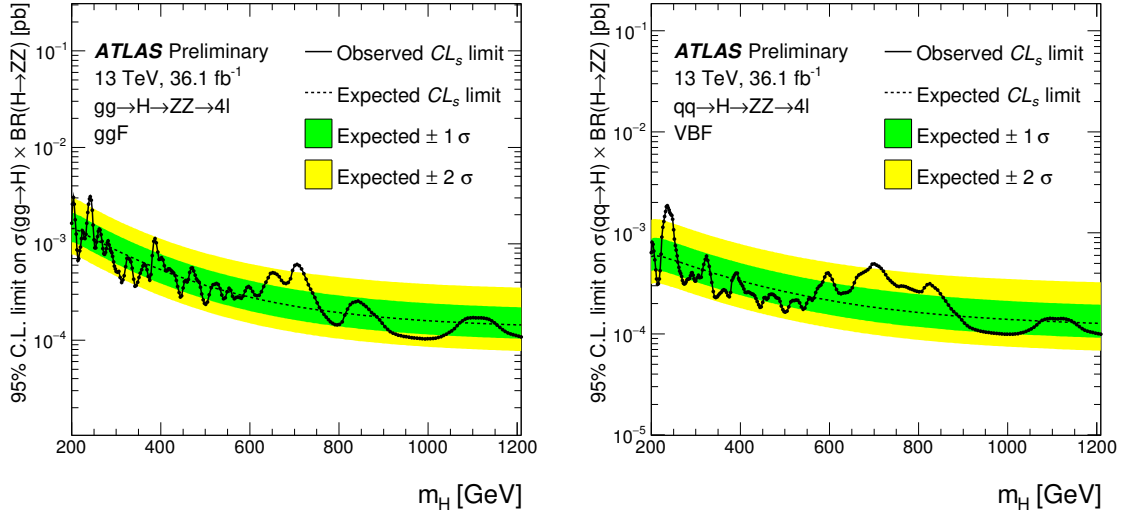


Figure 8.7: The upper limits at 95% confidence level on then $\sigma_{ggF} \times BR(S \rightarrow ZZ \rightarrow 4\ell)$ (left) and $\sigma_{VBF} \times BR(S \rightarrow ZZ \rightarrow 4\ell)$ (right) under the NWA.

Large Widths Assumption In the case of signal models under the LWA, limits on the cross section for the ggF production mode times branching ratio ($\sigma_{ggF} \times BR(H \rightarrow ZZ)$) are set for three benchmark widths of a heavy scalar. The interference between the heavy scalar and the SM Higgs boson, $H-h$, as well as the heavy scalar and the $gg \rightarrow ZZ^{(*)}$ continuum, $H-B$, are modeled by analytical functions as explained in Section 8.2. The total signal yields are parameterized as:

$$S = \mu \times S_{H\text{-only}} + \sqrt{\mu} \times (I_{H-B} + I_{H-h})$$

where μ is the signal strength modifier, $S_{\text{H-only}}$ is the expected number of events for heavy scalar signal only, and I_{H-B} and I_{H-h} are the yields of the corresponding interference terms. Figure 8.15 shows the limits for widths of 1%, 5% and 10% of m_H , respectively. The limits are set for masses of m_H higher than 400 GeV.

8.4.4 2HDM interpretation

A search in the context of a CP-conserving 2HDM, described in Section 2.4, is also presented. Figure 8.9 shows the exclusion limits in the $\cos(\beta - \alpha)$ versus $\tan \beta$ plane for Type-I and Type-II 2HDMs, for a heavy Higgs boson with a mass of 200 GeV. This mass value is chosen so that the assumption of a narrow-width Higgs boson is valid over most of the parameter space, and the experimental sensitivity is maximal. The range of $\cos(\beta - \alpha)$ and $\tan \beta$ presented is limited to the region where both the assumption of a heavy narrow-width Higgs boson and the perturbativity in calculating the cross section are valid. The upper limits at a given value of $\cos(\beta - \alpha)$ and $\tan \beta$ are re-calculated by using the predicted ratio of ggF production rate over VBF. Figure 8.10 shows the exclusion limits in the $\cos(\beta - \alpha)$ versus m_H plane for $\cos(\beta - \alpha) = -0.1$. The valid range of $\cos(\beta - \alpha)$ is constrained by the measurement of the coupling of the SM Higgs boson with the Z-boson (κ_h), which is proportional to $\sin(\beta - \alpha)$. From the combined measurement of Higgs couplings at LHC [164], the measured κ_h is consistent with the SM prediction within the uncertainty of about 7%, therefore the chosen $\cos(\beta - \alpha)$ is valid.

The hatched red area in this exclusion plots is the excluded parameter space. Compared with the results presented in Run 1 [20], the exclusion limits presented here is almost twice more stringent.

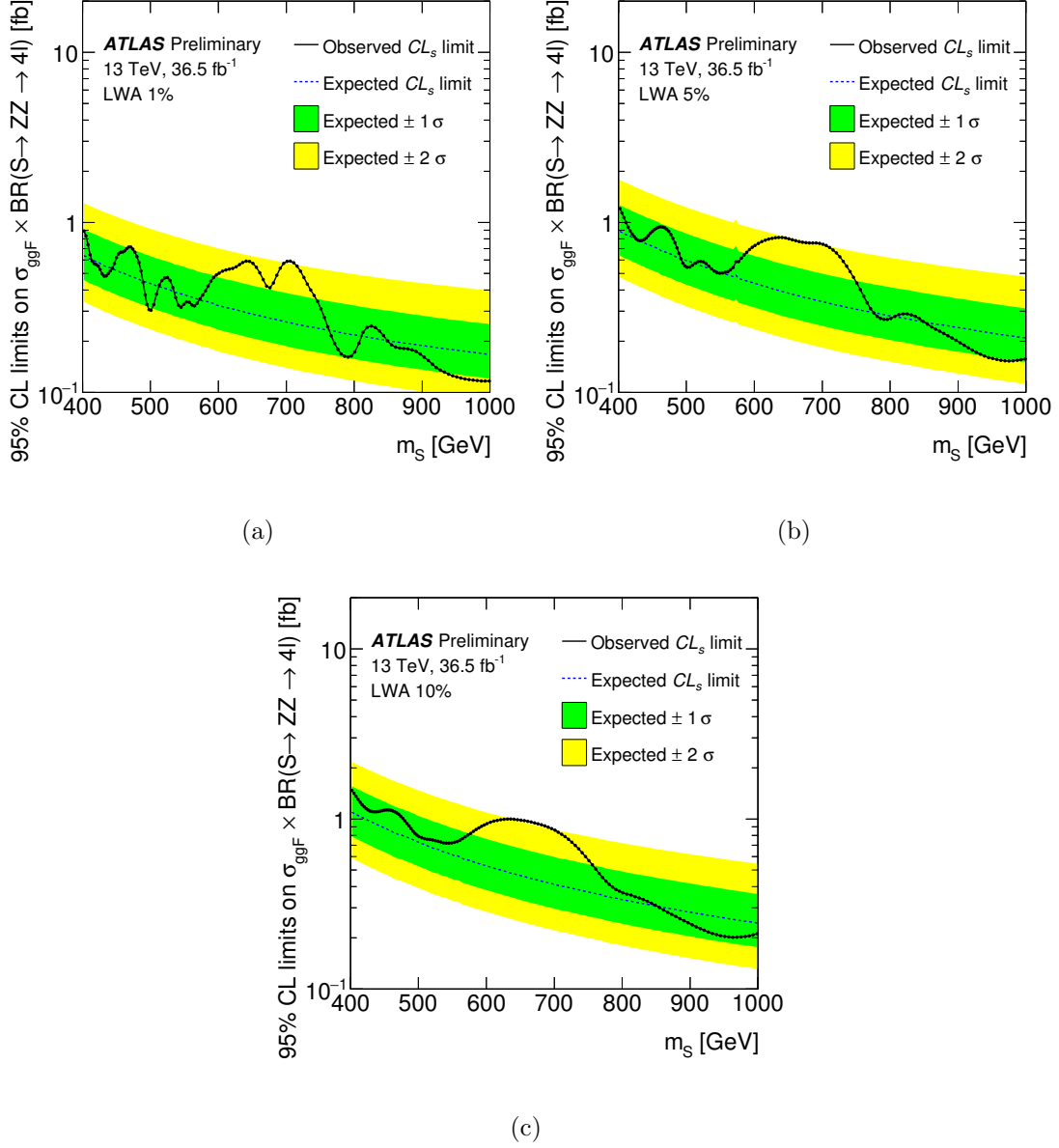


Figure 8.8: 95% confidence level limits on cross section for ggF production mode times the branching ratio ($\sigma_{\text{ggF}} \times \text{BR}(H \rightarrow ZZ \rightarrow 4\ell)$) as function of m_H for an additional heavy scalar assuming a width of 1% (a), 5% (b) and 10% (c) of m_H . The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits.

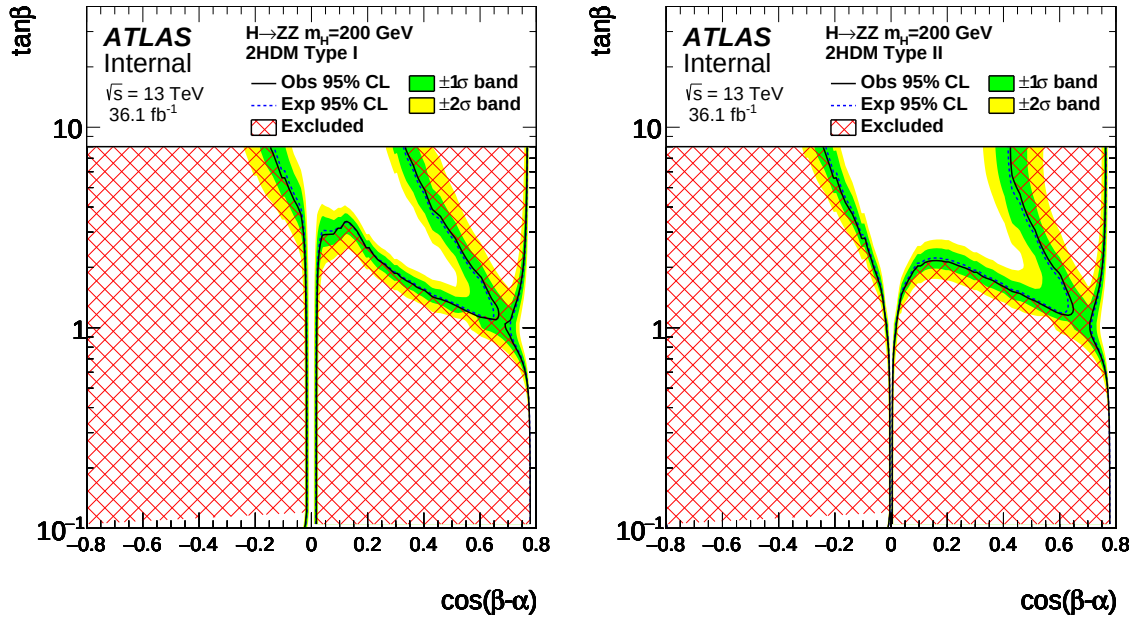


Figure 8.9: The exclusion contour in the plane of $\tan\beta$ and $\cos(\beta - \alpha)$ for $m_H = 200$ GeV for Type-I and Type-II. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The hatched area shows the observed exclusion.

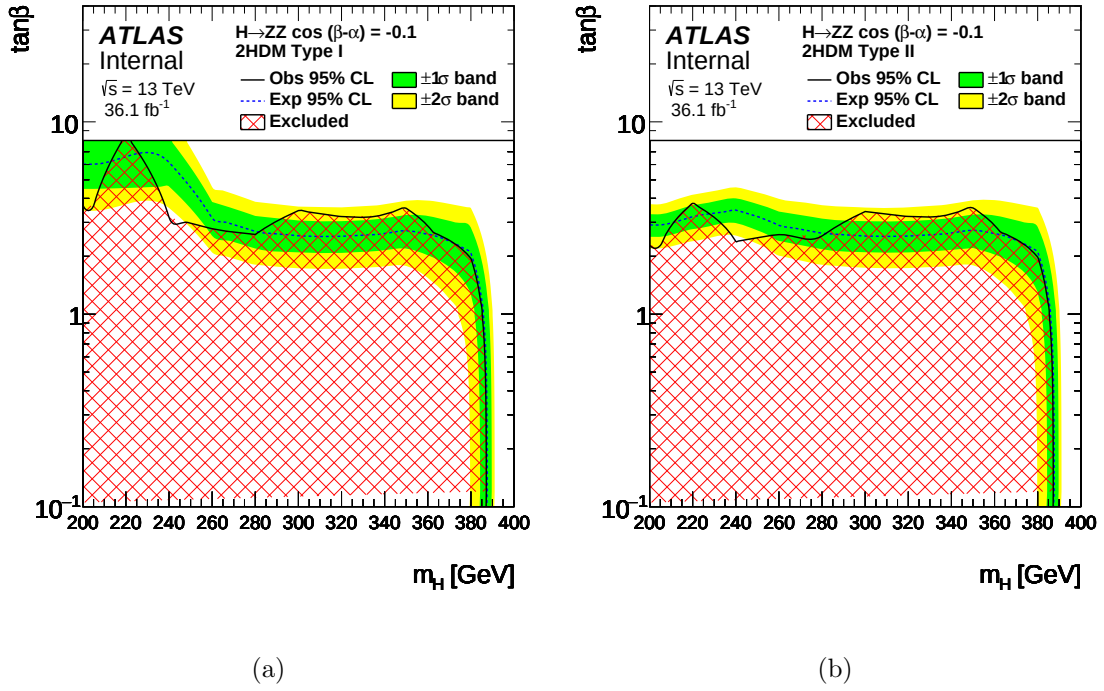


Figure 8.10: The exclusion limits as a function of $\tan\beta$ and m_H with $\cos(\beta-\alpha) = -0.1$ for Type-I (a) and Type-II (b) 2HDM. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The hatched area shows the observed exclusion.

8.5 Combination of the results from $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$

The $\ell^+\ell^-\ell^+\ell^-$ final state features excellent mass resolution while the $\ell^+\ell^-\nu\bar{\nu}$ benefits from a larger branching ratio. The $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ analyses compliment each other when they are combined, leading to better search sensitivities over the whole mass range. Section 8.5.1 provides an overview of the search for heavy resonances in the $\ell^+\ell^-\nu\bar{\nu}$ final state. Section 8.5.2 describes the correlation schemes used in the combination, Section 8.5.3 discusses the impact of the uncertainties on the signal cross section and Section 8.5.4 shows the combined results.

8.5.1 Search for heavy resonances in the $\ell^+\ell^-\nu\bar{\nu}$ final state

The search for heavy resonances in the $\ell^+\ell^-\nu\bar{\nu}$ final state selects the events that contain two oppositely charged isolated leptons originating from an on-shell Z boson along with a large missing transverse momentum (E_T^{miss}). Different assumptions of the origin of E_T^{miss} lead to different signal models, therefore the $\ell^+\ell^-\nu\bar{\nu}$ final state is sensitive to different signal models. For example, it is sensitive to the Higgs boson decays to invisible particles when E_T^{miss} is assumed to come from the invisible decay of the Higgs boson, and sensitive to the dark matter production rate when E_T^{miss} is assumed to come from dark particles that form dark matter. The two results are reported in Ref. [165], using 36.1 fb^{-1} pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected by ATLAS. However, in this thesis, E_T^{miss} is presumably from the neutrinos that have decayed from the Z boson. For two on-shell Z bosons, the branching ratio of $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ is 4.044% and that of $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ is 0.452%, where ℓ stands for e or μ .

This search looks for an excess in the transverse mass spectrum m_T , defined as:

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} \right]^2 - \left| \vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}} \right|^2} \quad (8.1)$$

where m_Z is the pole mass of the Z boson, $p_T^{\ell\ell}$ is the transverse momentum of the lepton pair, $\vec{E}_T^{\text{miss}}$ is the missing transverse momentum and E_T^{miss} is the magnitude of $\vec{E}_T^{\text{miss}}$.

Event Selections The event selections are designed to discriminate against the Z + jets, WZ and top-quark backgrounds. Events are required to pass either a single electron or muon trigger, where different p_T thresholds are used depending on the instantaneous luminosity of the LHC. The trigger efficiency for signal events passing the final selection is about 99%. Selected events must have exactly two opposite-charge leptons of the same flavor and “medium” identification, with the more energetic lepton having $p_T > 30$ GeV and the other one having $p_T > 20$ GeV. The same impact parameter significance criteria as defined in Chapter 6 are applied to the selected leptons. Track- and calorimeter-based isolation criteria as defined in Chapter 6 are also applied to the leptons, but in this analysis the criteria are optimized by adjusting the isolation threshold so that the selection efficiency of the isolation criteria is 99% for signal leptons. If an additional lepton with $p_T > 7$ GeV and “loose” identification is found then the event is rejected, to reduce the amount of the WZ background. In order to select leptons originating from the decay of a Z boson, the invariant mass of the lepton pair is required to be in the range of 76 to 106 GeV. Moreover, since a Z boson originating from the decay of a high-mass particle will be boosted, the two leptons are required to be produced with a small angular separation $\Delta R_{\ell\ell} < 1.8$.

Events with neutrinos in the final state are selected by imposing $E_T^{\text{miss}} > 120 \text{ GeV}$, and this requirement heavily reduces the amount of $Z + \text{jets}$ background. In signal events with no initial- or final-state radiation the Z boson is expected to be produced back-to-back with respect to the missing transverse momentum, and this characteristic is used to further suppress the $Z + \text{jets}$ background. The azimuthal angle between the dilepton system and the missing transverse momentum ($\Delta\Phi(\ell\ell, \vec{E}_T^{\text{miss}})$) is thus required to be greater than 2.7 and the fractional p_T difference, defined as $|p_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, to be less than 20%, where $p_T^{\text{miss,jet}} = |\vec{E}_T^{\text{miss}} + \sum_{\text{jet}} \vec{p}_T^{\text{jet}}|$.

Additional selection criteria are applied to keep only events with E_T^{miss} originating from neutrinos rather than detector inefficiencies, poorly reconstructed high- p_T muons or mis-measurements in the hadronic calorimeter. If at least one reconstructed jet has a p_T greater than 100 GeV, the azimuthal angle between the highest- p_T jet and the missing transverse momentum is required to be greater than 0.4. Similarly, if E_T^{miss} is found to be less than 40% of the scalar sum of the transverse momenta of leptons and jets in the event (H_T), the event is rejected. Finally, to reduce the $t\bar{t}$ background, events are rejected whenever a b-jet is found.

The sensitivity of the analysis to the VBF production mode is increased by creating a dedicated category of VBF-enriched events. An optimization procedure based on the significance obtained by using signal and background MC samples is performed and the selection criteria require the presence of at least two jets with $p_T > 30 \text{ GeV}$ checking that the two highest- p_T jets are widely separated in η , $|\Delta\eta_{jj}| > 4.4$, and have a invariant mass m_{jj} greater than 500 GeV.

The signal acceptance, defined as the ratio of the number of reconstructed events passing the analysis requirements to the number of simulated events in each category,

for the $\ell^+\ell^-\nu\bar{\nu}$ analysis is shown in Table 8.2, for the ggF and VBF production modes as well as for different resonance masses.

Table 8.2: Signal acceptance for the $\ell^+\ell^-\nu\bar{\nu}$ analysis, for both the ggF and VBF production modes and resonance masses of 300 and 600 GeV. The acceptance is defined as the ratio of the number of reconstructed events after all selection requirements to the number of simulated events for each channel/category.

Mass	Production mode	ggF-enriched categories		VBF-enriched category
		$\mu^+\mu^-$ channel	e^+e^- channel	
300 GeV	ggF	6%	5%	< 0.05% 0.7%
	VBF	2.6%	2.4%	
600 GeV	ggF	44%	44%	1%
	VBF	27%	27%	13%

The $\ell^+\ell^-\nu\bar{\nu}$ search starts only from 300 GeV because this is where it begins to improve the combined sensitivity as the acceptance increases due to a kinematic threshold coming from the E_T^{miss} selection criteria, also seen from Table 8.2.

Background Estimation The dominant and irreducible background for this search is the non-resonant ZZ production which accounts for about 60% of the expected background events. The second largest background comes from the WZ production ($\sim 30\%$) followed by $Z + \text{jets}$ production with poorly measured jets ($\sim 6\%$). Other sources of background are the WW , $t\bar{t}$, Wt and $Z \rightarrow \tau\tau$ processes ($\sim 3\%$). Finally, a small contribution comes from $W + \text{jets}$, single-top quark and multi-jet processes, with at least one jet mis-identified as an electron or muon, as well as from $t\bar{t}V/VVV$ events.

The ZZ production is modeled with MC simulation and normalized to SM predictions, as explained in Section 4.2. The remaining backgrounds are mostly estimated

by extrapolating the events in a control region to the signal region using dedicated transfer factors.

The WZ background is modeled by MC simulation and a correction factor for its normalization is extracted as the ratio of data events to the simulated events in a WZ -enriched control region, after subtracting from data the non- WZ background contribution. The WZ -enriched control region, called the 3ℓ control region, is built by selecting $Z \rightarrow \ell\ell$ candidates with an additional electron or muon. This additional lepton is required to pass all selection criteria used for the other two leptons, with the only difference that its transverse momentum is required to be greater than 7 GeV. The contamination from $Z + \text{jets}$ and $t\bar{t}$ events is reduced by vetoing events with at least one reconstructed b-jet and by requiring the transverse mass of W boson (m_T^W), built using the additional lepton and the $\vec{E}_T^{\text{miss}}$, to be greater than 60 GeV. The distribution of the missing transverse momentum for data and simulated events in the 3ℓ control region is shown in Figure 8.11(a). The correction factor derived in the 3ℓ control region is found to be 1.29 ± 0.09 , where the uncertainty includes effects from the statistics of the control region as well as from experimental systematic uncertainties. Due to poor statistics when applying all the VBF selection requirements to the WZ enriched control sample, the estimate for the VBF-enriched category is performed by including in the 3ℓ control region only the requirement of at least two jets with $p_T > 30$ GeV. Finally, a transfer factor is derived from MC simulation by calculating the probability of events passing all analysis selections and containing two jets with $p_T > 30$ GeV to satisfy the VBF selections

The non-resonant background includes mainly WW , $t\bar{t}$ and Wt processes, but also $Z \rightarrow \tau\tau$ events in which the τ leptons produce light leptons and E_T^{miss} . It is

estimated by using a control sample of events with lepton pairs of different flavour ($e^\pm\mu^\mp$), passing all analysis selection criteria. Figure 8.11(b) shows the missing transverse momentum distribution for $e^\pm\mu^\mp$ events in data and simulation after applying the dilepton invariant mass selection but before applying the other selection requirements. The non-resonant background in the e^+e^- and $\mu^+\mu^-$ channels is estimated by applying a scale factor (f) to the events in the $e^\pm\mu^\mp$ control region, such that:

$$N_{ee}^{\text{bkg}} = \frac{1}{2} \times N_{e\mu}^{\text{data,sub}} \times f, \quad N_{\mu\mu}^{\text{bkg}} = \frac{1}{2} \times N_{e\mu}^{\text{data,sub}} \times \frac{1}{f}, \quad (8.2)$$

where N_{ee}^{bkg} and $N_{\mu\mu}^{\text{bkg}}$ are the numbers of electron and muon pair events estimated in the signal region and $N_{e\mu}^{\text{data,sub}}$ is the number of events in the $e^\pm\mu^\mp$ control sample with ZZ , WZ and other small backgrounds subtracted using simulation. The factor f takes into account the different selection efficiency of e^+e^- and $\mu^+\mu^-$ pairs at the level of the $Z \rightarrow \ell\ell$ selection, and is measured from data as $f^2 = N_{ee}^{\text{data}}/N_{\mu\mu}^{\text{data}}$, where N_{ee}^{data} and $N_{\mu\mu}^{\text{data}}$ are the number of events passing the Z boson mass requirement ($76 < m_{\ell\ell} < 106$ GeV) in the electron and muon channel respectively. As no events survive in the $e^\pm\mu^\mp$ control region after applying the full VBF selections, the background estimate is performed by including only the requirement of at least two jets with $p_T > 30$ GeV. The efficiency of the remaining selection criteria on $\Delta\eta_{jj}$ and m_{jj} is obtained from simulated events.

The number of Z + jets background events in the signal region is estimated from data, using a so-called ABCD method [166], since events with no genuine E_T^{miss} in the final state are difficult to model using simulation. The method combines the selection requirements presented in Section 8.5.1 (with $n_{b\text{-jets}}$ representing the number of b -jets in the event) into two Boolean discriminants, V_1 and V_2 , defined as:

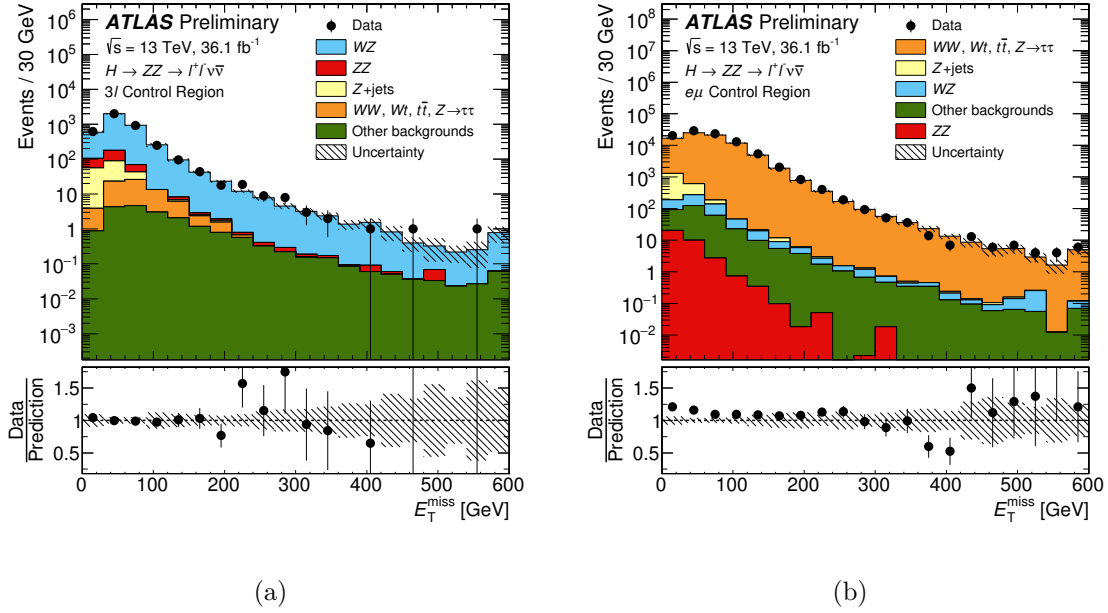


Figure 8.11: Missing transverse momentum distribution (a) for events in the 3ℓ control region as defined in the text and (b) for $e^\pm\mu^\mp$ lepton pairs after applying the dilepton invariant mass selection. The backgrounds are determined following the description in Section 8.5.1 and the last bin includes the overflow. The error bars on the data points indicate the statistical uncertainty, while the systematic uncertainty on the prediction is shown by the hatched band. The bottom part of the figures shows the ratio of data over expectation.

$$V_1 \equiv E_T^{\text{miss}} > 120 \text{ GeV and } E_T^{\text{miss}}/H_T > 0.4, \quad (8.3)$$

$$V_2 \equiv |p_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2 \text{ and } \Delta\phi(\ell\ell, \vec{E}_T^{\text{miss}}) > 2.7 \text{ and } \Delta R_{\ell\ell} < 1.8 \text{ and } n_{b\text{-jets}} = 0, \quad (8.4)$$

with all events required to pass the trigger and dilepton invariant mass selections. The signal region (A) is thus obtained by requiring both V_1 and V_2 to be true, control regions B and C require only one of the two booleans to be false (V_1 and V_2 respectively) and finally control region D is defined by requesting both V_1 and V_2 to be false. With this definition, an estimate of the number of events in region A is given by $N_A^{\text{est}} = N_C^{\text{obs}} \times (N_B^{\text{obs}}/N_D^{\text{obs}})$, where N_X^{obs} is the number of events observed in region X after subtracting non- Z -boson backgrounds. This relation holds as long as the correlation between V_1 and V_2 is small, and this is obtained by introducing two additional requirements on control regions B and D, namely $E_T^{\text{miss}} > 30 \text{ GeV}$ and $E_T^{\text{miss}}/H_T > 0.1$. The estimation of the $Z + \text{jets}$ background was cross-checked with another approach in which a control region is defined by inverting the analysis selection on E_T^{miss}/H_T and then using $Z + \text{jets}$ Monte Carlo simulation to perform the extrapolation to the signal region, yielding results compatible with the ABCD method. Finally, the estimate for the VBF-enriched category is performed by extrapolating the inclusive result obtained with the ABCD method to the VBF signal region, extracting the efficiency of the two-jet, $\Delta\eta_{jj}$ and m_{jj} selection criteria from $Z + \text{jets}$ simulation.

The $W + \text{jets}$ and multi-jet backgrounds are estimated from data using a so-called fake factor method [167]. A control region enriched in fake leptons is designed by requiring one lepton to pass all analysis requirements (baseline selection) and the other

one to fail either the lepton “medium” identification or the isolation criteria (inverted selection). The background in the signal region is then derived using a transfer factor, measured in a data sample enriched in $Z + \text{jets}$ events, as the ratio of jets passing the baseline selection to those passing the inverted selection.

Finally, the background from the $t\bar{t}V$ and VVV processes is estimated using MC simulation.

Signal and background modelling The modeling of the transverse invariant mass m_T distribution for signal and background is based on the templates derived from fully simulated events and afterwards used to fit the data. In the case of a narrow width resonance, simulated MC events generated at fixed mass hypotheses as described in Section 4.2 are used as the inputs in the moment morphing technique [168] to obtain the m_T distribution for any other mass hypothesis.

The extraction of the interference terms for the LWA case is performed in the same way as in the $\ell^+\ell^-\ell^+\ell^-$ final state, as described in Section 8.2. In the case of the $\ell^+\ell^-\nu\bar{\nu}$ final state a correction factor, extracted as a function of m_{ZZ} , is used to reweight the interference distributions obtained at particle-level to account for reconstruction effects. The final expected LWA m_T distribution is obtained from the combination of the interference distributions with simulated m_T distributions, which are interpolated between the simulated mass points with a weighting technique using the Higgs propagator, a similar method to that used for the interference.

Results Table 8.3 contains the number of observed candidate events along with the background yields for the $\ell^+\ell^-\nu\bar{\nu}$ analysis, while Figure 8.12 shows the m_T distribution

for the electron and muon channels with the ggF-enriched and VBF-enriched categories combined.

Table 8.3: $\ell^+\ell^-\nu\bar{\nu}$ search: Number of expected and observed events together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

Process	ggF-enriched categories		VBF-enriched category
	e^+e^- channel	$\mu^+\mu^-$ channel	
ZZ	$177 \pm 3 \pm 21$	$180 \pm 3 \pm 21$	$2.1 \pm 0.2 \pm 0.7$
WZ	$93 \pm 2 \pm 4$	$99.5 \pm 2.3 \pm 3.2$	$1.29 \pm 0.04 \pm 0.27$
$WW/t\bar{t}/Wt/Z \rightarrow \tau\tau$	$9.2 \pm 2.2 \pm 1.4$	$10.7 \pm 2.5 \pm 0.9$	$0.39 \pm 0.24 \pm 0.26$
$Z + \text{jets}$	$17 \pm 1 \pm 11$	$19 \pm 1 \pm 17$	$0.8 \pm 0.1 \pm 0.5$
Other backgrounds	$1.12 \pm 0.04 \pm 0.08$	$1.03 \pm 0.04 \pm 0.08$	$0.03 \pm 0.01 \pm 0.01$
Total background	$297 \pm 4 \pm 24$	$311 \pm 5 \pm 27$	$4.6 \pm 0.4 \pm 0.9$
Observed	320	352	9

8.5.2 Correlation schemes

The combined results are based on a simultaneous fit among different signal regions defined separately for each analysis. To avoid double-counting, the orthogonality among signal regions is ensured when designing the analysis. The systematic uncertainties, represented by nuisance parameters, are properly correlated. The experimental systematic uncertainties due to the same sources are fully correlated between/within the two analyses. The uncertainties on QCD scale are uncorrelated for the ggF/VBF signal productions and the $ZZ^{(*)}$ continuum backgrounds, as the three processes are evaluated in different QCD scales; but the uncertainties are correlated for the $q\bar{q} \rightarrow ZZ^{(*)}$ and the $gg \rightarrow ZZ^{(*)}$ background. The uncertainties on the parton distribution functions are fully correlated for the ggF signal production and the

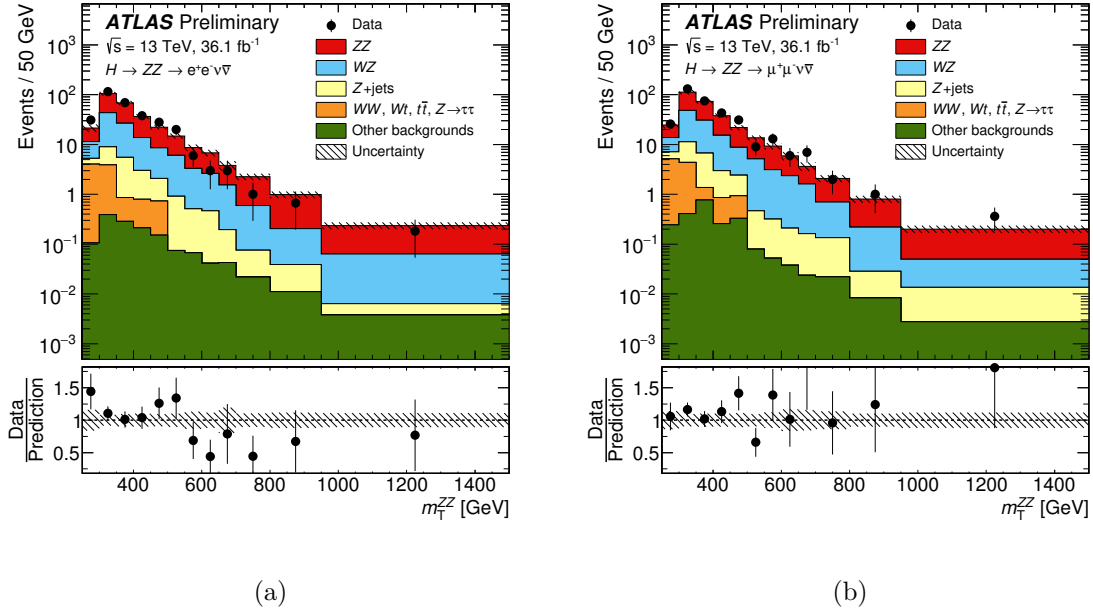


Figure 8.12: Transverse invariant mass distribution in the $\ell^+\ell^-\nu\bar{\nu}$ search for (a) the electron channel and (b) the muon channel, including events from both the ggF-enriched and the VBF-enriched categories. The backgrounds are determined following the description in Section 8.5.1 and the last bin includes the overflow. The error bars on the data points indicate the statistical uncertainty and markers are drawn at the bin centre. The systematic uncertainty on the prediction is shown by the hatched band. The bottom part of the figures shows the ratio of data over expectation.

$gg \rightarrow ZZ^{(*)}$ background as well as for VBF signal production and the $q\bar{q} \rightarrow ZZ^{(*)}$ background. The uncertainties resulting from data-driven methods are uncorrelated. A given correlated uncertainty is modeled in the fit by using a nuisance parameter common to all of the searches.

8.5.3 Impact of the uncertainties on signal cross section

The impact of a systematic uncertainty on the result depends on the production mode and the mass hypothesis. For the ggF production, at lower masses the luminosity uncertainty, the modeling uncertainty of the Z boson with associated jets background and the statistical uncertainty in $e\mu$ control region of the $\ell^+\ell^-\nu\bar{\nu}$ final state dominate, and at higher masses the uncertainties on the electron isolation efficiency become important, as seen also in the VBF production. For the VBF production, the dominant uncertainties come from the showering uncertainties and theoretical predictions of the ZZ events in the VBF category. Additionally at lower masses, the pileup reweighting and the jet energy resolution uncertainties are also important. Table 8.4 shows the impact of the leading systematic uncertainties on the signal cross section, which is set to the expected upper limit, for ggF production and VBF production. The impact of the uncertainty from the integrated luminosity, 3.2%, enters both in the normalization of the fitted number of signal events as well as in the background expectation from simulation. This leads to a luminosity uncertainty which varies from 4% to 7% across the mass distribution, depending on the signal to background ratio.

Table 8.4: Impact of the leading systematic uncertainties on the predicted signal event yield which is set to the expected upper limit, expressed as a percentage of the cross section for the ggF (left) and VBF (right) production modes at $m_H = 300, 600$, and 1000 GeV.

ggF production		VBF production	
Systematic source	Impact [%]	Systematic source	Impact [%]
$m_H = 300$ GeV			
Luminosity	4	Parton showering	9
Z +jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	3.3	Jet energy scale	4
Parton showering	3.2	Luminosity	4
$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$	3.2	$q\bar{q} \rightarrow ZZ^{(*)}$ QCD scale (VBF-enriched category)	4
$m_H = 600$ GeV			
Luminosity	6	Parton showering	6
Pileup reweighting	5	Pileup reweighting	6
Z +jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4	Jet energy scale	6
QCD scale of $q\bar{q} \rightarrow ZZ^{(*)}$	3.1	Luminosity	4
$m_H = 1000$ GeV			
Luminosity	4	Parton showering	6
QCD scale of $gg \rightarrow ZZ^{(*)}$	2.3	Jet energy scale	5
Jet vertex tagger	1.9	Z +jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4
Z +jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	1.8	Luminosity	4

8.5.4 Combination results

The excess observed in the $\ell^+\ell^-\ell^+\ell^-$ search at a mass around 700 GeV is excluded at 95% confidence level by the $\ell^+\ell^-\nu\bar{\nu}$ search, which is more sensitive in this mass range. The excess at 240 GeV is not covered by the $\ell^+\ell^-\nu\bar{\nu}$ search, the sensitivity of which starts from 300 GeV. When combining the results from the two final states, the largest deviation with respect to the background expectation is observed around 700 GeV with a global significance of less than 1σ and a local significance of about 2σ . The combined yield of the two final states is 1870 events observed in data compared to 1643 ± 164 (combined statistical and systematic uncertainty) for the total expected backgrounds. This corresponds to a 1.3σ global excess in data. Since no significant excess is found, the results are interpreted as upper limits on the production cross section of a scalar resonance. The local p -value for $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ as well as their combination derived for a narrow resonance and assuming the signal comes only from the ggF production is shown in Figure 8.13 as a function of the resonance mass m_H between 200 GeV and 1200 GeV.

NWA interpretation Upper limits on the cross section times branching ratio ($\sigma \times BR(H \rightarrow ZZ)$) for a heavy resonance are obtained as a function of m_H with the CL_s procedure [149] in the asymptotic approximation from the combination of the two final states. It is assumed that an additional heavy scalar would be produced predominantly via the ggF and VBF processes but that the ratio of the two production mechanisms is unknown in the absence of a specific model. For this reason, fits for the ggF and VBF production processes are done separately, and in each case the other process is allowed to float in the fit as an additional nuisance parameter. Figure 8.14 presents

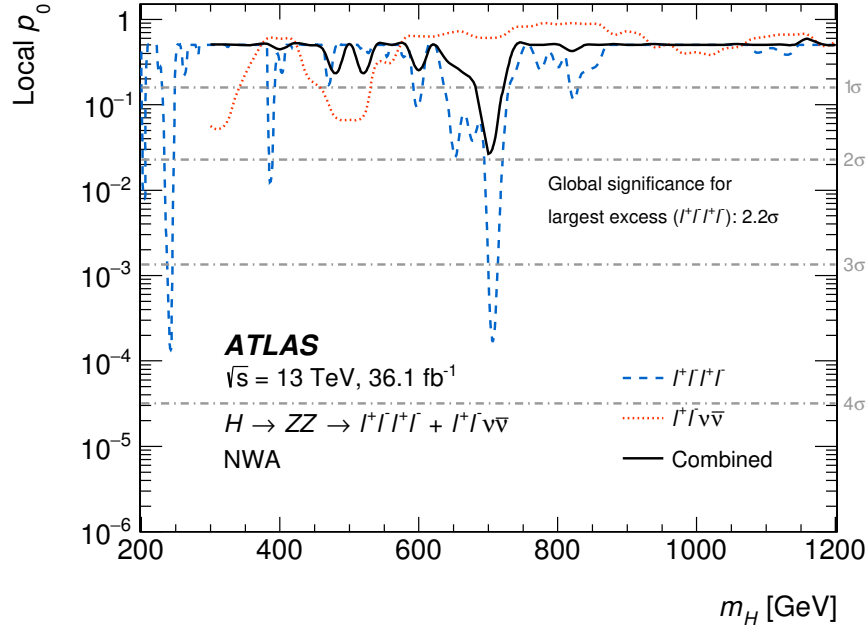


Figure 8.13: Local p_0 for $\ell^+\ell^-\ell^+\ell^-$ (blue, dashed line) and $\ell^+\ell^-\nu\bar{\nu}$ (red, dotted line) final states as well as for their combination (black line) derived for a narrow resonance and assuming the signal comes only from the ggF production, as a function of the resonance mass m_H between 200 GeV and 1200 GeV. Also shown are local (dot-dashed line) significance levels.

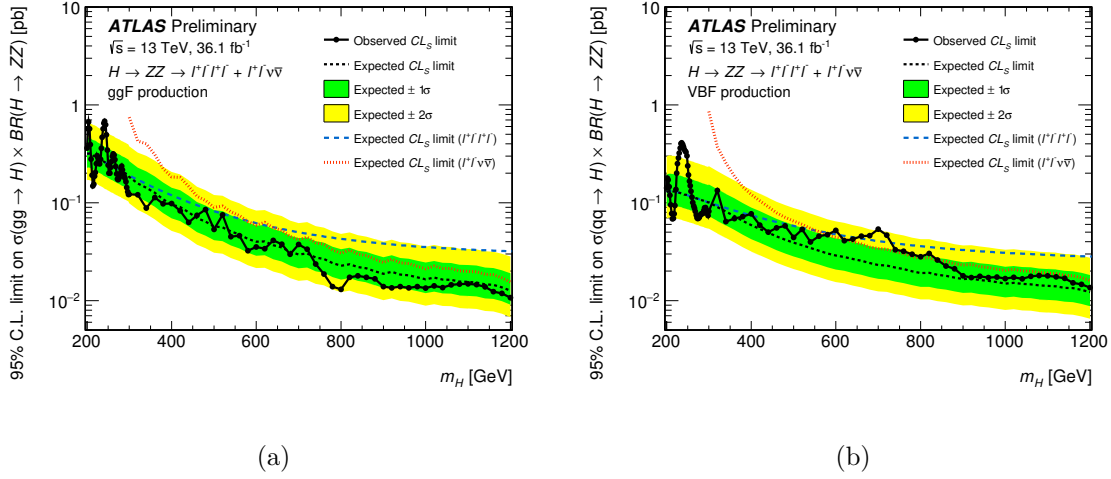


Figure 8.14: The upper limits at 95% confidence level on the cross section times branching ratio for (a) the ggF production mode ($\sigma_{\text{ggF}} \times BR(H \rightarrow ZZ)$) and (b) for the VBF production mode ($\sigma_{\text{VBF}} \times BR(H \rightarrow ZZ)$) in the case of NWA. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The dashed coloured lines indicate the expected limits obtained from the individual searches.

the expected and observed limits at 95% confidence level on $\sigma \times BR(H \rightarrow ZZ)$ of a narrow-width scalar for the ggF (left) and VBF (right) production modes, as well as the expected limits from the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ searches. This result is valid for models in which the width is less than 0.5% of m_H . When combining both final states, the 95% CL upper limits range from 0.68 pb at $m_H = 242$ GeV to 11 fb at $m_H = 1200$ GeV for the gluon fusion production mode and from 0.41 pb at $m_H = 236$ GeV to 13 fb at $m_H = 1200$ GeV for the vector boson fusion production mode. Compared with the results presented in Run 1 [20] where all four final states of ZZ decays were combined, the exclusion region presented here is significantly extended, depending on the heavy scalar mass tested.

LWA interpretation In the case of the LWA, limits on the cross section for the ggF production mode times branching ratio ($\sigma_{\text{ggF}} \times BR(H \rightarrow ZZ)$) are set for different widths of the heavy scalar. The interference between the heavy scalar and the SM Higgs boson, H - h , as well as the heavy scalar and the $gg \rightarrow ZZ^{(*)}$ continuum, H - B , are modelled by either analytical functions or reweighting the signal-only events as explained in Sections 8.2 and 8.5.1. Figures 8.15(a), 8.15(b), and 8.15(c) show the limits for a width of 1%, 5% and 10% of m_H respectively. The limits are set for masses of m_H higher than 400 GeV.

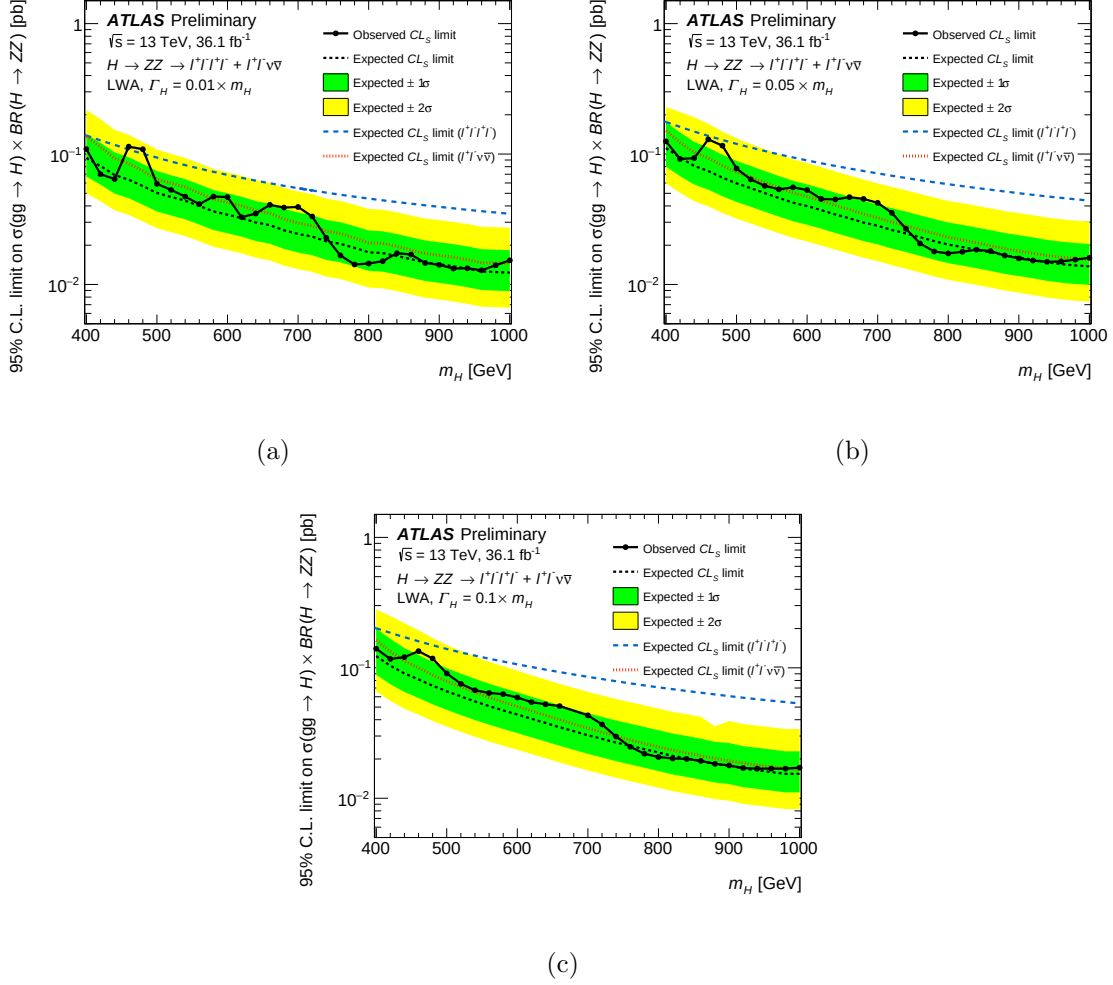


Figure 8.15: The 95% confidence level limits on the cross section for the ggF production mode times branching ratio ($\sigma_{\text{ggF}} \times \text{BR}(H \rightarrow ZZ)$) as function of m_H for an additional heavy scalar assuming a width of (a) 1%, (b) 5%, and (c) 10% of m_H . The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The dashed coloured lines indicate the expected limits obtained from the individual searches.

Chapter 9

Conclusion

The observation of the SM Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ is presented. It uses pp collision data corresponding to integrated luminosities of 4.5 fb^{-1} and 20.3 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$, respectively, recorded with the ATLAS detector at the LHC. In the mass range $120 - 130 \text{ GeV}$, 37 events are observed while 26.5 ± 1.7 events are expected, decomposed as 16.2 ± 1.6 events for a SM Higgs signal with $m_H = 125 \text{ GeV}$, $7.4 \pm 0.4 \text{ } ZZ^{(*)}$ background events and 2.9 ± 0.3 reducible background events. This excess corresponds to a $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$ signal observed (expected) with a significance of 8.1 (6.2) standard deviations at the combined ATLAS measurement of the Higgs boson mass, $m_H = 125.36 \text{ GeV}$ [152]. Furthermore, the mass and different production rates of the observed Higgs boson is measured. The mass measured in the $\ell^+\ell^-\ell^+\ell^-$ final state using the LHC Run 1 data is $m_H = 125.51 \pm 0.52 \text{ GeV}$. The gluon fusion signal strength is found to be $1.66^{+0.45}_{-0.41}(\text{stat})^{+0.25}_{-0.51}(\text{syst})$ and the signal strength for vector-boson fusion is found to be $0.26^{+1.60}_{-0.91}(\text{stat})^{+0.36}_{-0.23}(\text{syst})$. The measured signal strength is consistent with the SM expected values.

In the light of the observation of the SM Higgs boson, a search is presented for additional heavy scalars decaying into a pair of Z bosons which decay subsequently to $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states. The search uses proton–proton collision data collected with the ATLAS detector during 2015 and 2016 at the Large Hadron Collider at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.1 fb^{-1} . The results of the search are interpreted as upper limits on the production cross section of a spin-0 resonance. The mass range of the hypothetical resonances considered is between 200 GeV and 2000 GeV depending on the final state, and the model considered. The spin-0 resonance is assumed to be a heavy scalar, whose dominant production modes are gluon fusion and vector boson fusion. In a model independent approach the spin-0 resonance is studied in the Narrow Width Approximation and the Large Width Assumption. In the case of the Narrow Width Approximation, limits on the production rate of a heavy scalar decaying into two Z bosons are set separately for gluon fusion and vector boson fusion production modes. Combining both final states, 95% CL upper limits range from 0.68 pb at $m_H = 242 \text{ GeV}$ to 11 fb at $m_H = 1200 \text{ GeV}$ for the gluon fusion production mode and from 0.41 pb at $m_H = 236 \text{ GeV}$ to 13 fb at $m_H = 1200 \text{ GeV}$ for the vector boson fusion production mode. The results are also interpreted in the context of Type-I and Type-II two-Higgs-doublet models, with exclusion contours given in the $\cos(\beta - \alpha)$ versus $\tan \beta$ (for $m_H = 200 \text{ GeV}$) and m_H versus $\tan \beta$ planes. This m_H value is chosen so that the assumption of a narrow-width Higgs boson is valid over most of the parameter space and the experimental sensitivity is maximum. The limits on the production rate of a large-width scalar are obtained for widths of 1%, 5% and 10% of the mass of the resonance, with the interference between the heavy scalar and the SM Higgs boson as well as the heavy scalar and the

$gg \rightarrow ZZ^{(*)}$ continuum taken into account.

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