

Standard Model Higgs boson searches in the weak boson decay channels with the ATLAS detector

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There are two possible outcomes:
if the result confirms the hypothesis,
then you've made a measurement,
if the result is contrary to the hypothesis,
then you've made a discovery.
— Enrico Fermi

To Lu...

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Nani gigantum humeris insidentes

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G. D. C.

Abstract

The search of the Standard Model Higgs boson decaying into a pair of weak bosons with the subsequent leptonic decay of the W or Z bosons is presented. The contributions achieved by this work range from the reevaluation of Higgs boson normalisation cross-sections, to the development of the analysis strategies using detailed Monte Carlo simulations and the search results for the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay mode based on 4.7 fb^{-1} of proton-proton collision data at $\sqrt{s} = 7 \text{ TeV}$ taken during 2011 by the ATLAS detector.

The computation of cross-sections values for Higgs boson production at centre-of-mass energies varying from 6 to 14 TeV, for the main production mechanisms at the LHC were documented for posterior usage among the Collaboration. Preliminary detector resolution studies on $Z \rightarrow \mu\mu$ events using early data collected by ATLAS are also described.

Simulation studies for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ and $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ channels included feasibility checks used to quantify the expected sensitivity of the analyses for various scenarios with different centre-of-mass energy, luminosity and detector calibration conditions. These results were part of the input that the Collaboration used to feed the schedule and plans of the LHC.

On the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel, upper limits on the Higgs boson production cross-section in a mass range between 200 and 900 GeV are set. With this channel by itself, the Standard Model Higgs boson particle is excluded at 95% confidence level in the mass range between 319 and 558 GeV. To complete the current picture of the Higgs boson searches in the ATLAS detector, a compilation of the different Higgs boson analyses performed by the ATLAS Collaboration are introduced. The Higgs boson existence is constrained to be in a narrow window between 122.5 GeV and 129 GeV with 95% confidence level; where an excess of 2.6σ local significance is observed.

Keywords: Higgs boson, LHC, ATLAS, Standard Model, Electro-weak symmetry breaking, ZZ and WW Higgs decay modes

Résumé

La recherche du boson de Higgs du modèle standard, se désintégrant en une paire de bosons faibles W où Z se désintégrant à leur tour leptoniquement, est présentée. Les contributions obtenus par ce travail, inclus la réévaluation des sections efficaces du boson de Higgs, le développement des stratégies d'analyse en utilisant des simulations Monté Carlo détaillées, ainsi que des résultats pour le mode de désintégration $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$, basée sur 4.7 fb^{-1} de données de collisions proton-proton à $\sqrt{s} = 7 \text{ TeV}$ collectés durant l'année 2011 par le détecteur ATLAS.

Le calcul des valeurs de sections efficaces pour les principaux mode de production du boson de Higgs du modèle standard au LHC pour des énergies dans le centre de masse variant de 6 à 14 TeV, sont documentés pour un usage postérieur au sein de la collaboration ATLAS. Des études de la résolution du spectromètre à muon de l'expérience ATLAS en utilisant des événements $Z \rightarrow \mu\mu$ pris lors du début de l'opération du détecteur à haut energie sont également décrits.

Les études de simulation Monté Carlo pour les canaux $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ et $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, inclus son faisabilité de telle analyses, la quantification de la sensibilité attendue pour différentes énergie dans le centre de masse, différente luminosité et différentes conditions de calibration du détecteur. Ces résultats faisaient partie de données collecté par la collaboration ATLAS et utilisée pour la mise en place du calendrier et des plans du LHC.

Pour les limites du canal $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$, une limite supérieur sur la section efficace de production du boson de Higgs dans une plage de masse comprise entre 200 et 900 GeV est présentée. Avec uniquement ce canal, le boson de Higgs du modèle standard est exclu à un niveau de 95% de confiance dans la gamme de masse allant de 319 à 558 GeV. Pour compléter l'état actuel des recherches du boson de Higgs du modèle standard avec détecteur ATLAS, la compilation des différentes analyses pour la recherche du boson de Higgs effectuées par la collaboration ATLAS sont introduits. L'existence du boson de Higgs du modèle standard est contraint à être dans une fenêtre en masse compris entre 122.5 GeV et 129 GeV à 95% de niveau de confiance, où un excès avec une significance locale de 2.5σ est observée.

Mots-clés : Le boson de Higgs, LHC, ATLAS, Modél Standard, brisure de symétrie électro-faible, ZZ et WW comme modes de désintégration du boson de Higgs

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Introduction



“Science is the belief in the ignorance of experts.”

Richard Feynman.

The Large Hadron collider (LHC) is a particle accelerator built at the European Organisation for Nuclear Research (CERN) which collides high energy proton beams recreating near-Big-Bang conditions. Among the different goals of the LHC, it is to probe the existence of new physics needed to satisfactorily explain observations and measurements that lie outside our current understanding of nature. In particular, the search of the Higgs boson particle which somehow became the flagship of high energy physics agenda.

The Higgs boson particle is the “missing-link” of the so called Standard Model (SM) theory [1–3], it is the manifestation responsible to give mass to each of the elementary particles, in particular to the charged and neutral electroweak currents, the W and Z bosons respectively. This theory has been extensively targeted and probed by a vast number of searches in many previous experiments. Up to early this year, the Higgs boson existence was constrained at a 95% Confidence Level (CL) to have a mass larger than 114 GeV by the Large Electron-Positron Collider (LEP) searches [4]. The Tevatron accelerator host of the DØ and CDF detectors, also excluded a SM Higgs boson in the window between 147-179 GeV [5, 6]. The Tevatron stopped operations on September 2011, leaving the LHC as the only experiment on earth able to hunt the Higgs boson.

The design and construction of the LHC and its detectors took several decades. A vast number of studies aimed to estimate the expected sensitivity reach of different searches as function of luminosity and centre-of-mass energy played a crucial role not only for the design of the experiment, but also for the optimisation of running-parameters and arrangement of operation schedules. Monte Carlo (MC) simulations have been a key aspect for the determination of these expectations; they are a vital input to the accelerator team which have to find a compromise of delivering a high intensity and energetic beam without compromising the reliability and health of the LHC, this was particularly important after the incident occurred

during the LHC start-up on September 2008 [7]

During 2010, the LHC successfully started its commissioning and physics programs colliding protons at a record centre of mass energy of $\sqrt{s} = 7$ TeV. It delivered a small but invaluable integrated luminosity of $\int \mathcal{L} dt = 40 \text{ pb}^{-1}$ which allowed the community to start the calibration phase of the detectors. During 2011 with a more stable machine and beam instantaneous luminosities starting from $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ up to $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, the ATLAS detector was able to collect a record integrated luminosity of about $\int \mathcal{L} dt = 5 \text{ fb}^{-1}$, 125 times what was recorded in 2010. This allows to set record constraints on the existence (or not) of the Higgs boson particle.

The content of this document is distributed as follows: Chapter 1 provides a brief summary of the Standard Model theory, the Higgs boson mechanism and the electroweak symmetry breaking theory. Chapter 2 describes more in detail the state-of-the-art estimations for the SM Higgs boson production cross-sections, and branching fractions including several high order corrections. In Chapter 3 the LHC with its detectors and in particular the ATLAS detector are introduced. The different subsystems and the technologies used by ATLAS to measure the different properties of particles passing through the detector are described. Chapter 4 delineates the main aspects of the MC simulations, from the event generation with parton level calculations to the detailed fully-simulated interaction of particles with the detector materials. In Chapter 5, results obtained with the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel using $\int \mathcal{L} dt = 4.7 \text{ fb}^{-1}$ of $\sqrt{s} = 7$ TeV data are presented as well as the results of the statistical combination of all of the Higgs boson searches obtained by the ATLAS collaboration with the 2011 dataset. Chapter 6 describes MC simulation studies, evaluated on different LHC and ATLAS running scenarios for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ and $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ channels.

1 Theory introduction



“The more the universe seems comprehensible, the more it also seems pointless.”

Steven Weinberg.

This chapter describes the main aspects of the Standard Model theory. It provides a short description of the electroweak symmetry breaking mechanism; as well as an introduction of the quark parton model formalism and the parton distribution functions parametrisation.

1.1 The Standard Model

The Theory of the Standard Model (SM) of elementary particle physics, successfully embeds electromagnetic, weak and strong interactions into the same structure. It consists of three generations of fermions together with several mediators gauge bosons plus the Higgs boson (see Fig. 1.1) with invariance under non-abelian local $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge transformations.

Leptons are defined as those fundamental particles with spin half-integer that carry no $SU(3)$ colour charge ($e, \mu, \tau; \nu_e, \nu_\mu, \nu_\tau$; with their correspondent anti-matter conjugates). Those other fermions that do carry a colour charge are defined as quarks (u, d, c, s, t, b ; plus their correspondent anti-matter conjugates). Free quarks have never been observed; they agglomerate inside colour neutral particles denominated hadrons. Hadrons are sub-categorised in mesons and baryons depending if they are made of two or three quarks. Gluons are massless vector gauge bosons that mediate the strong interactions of these quarks inside hadrons. Gluons are responsible for the strong force condensed under the so-called theory of quantum chromodynamics (QCD). In Sec. 1.3 of the present chapter some further details of the so-called quark parton model are given.

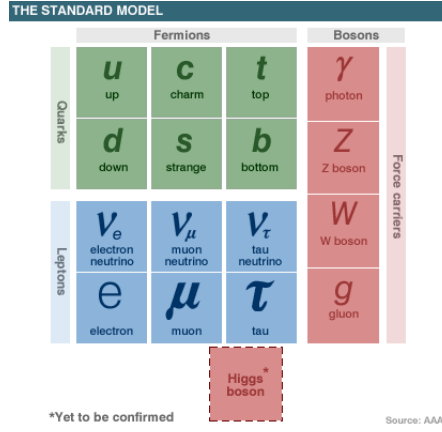


Figure 1.1: Particles in the SM.

The $SU(2)_L \otimes U(1)_Y$ accounts for the electroweak (EW) interactions. The weak interaction is known to violate parity symmetry acting exclusively on left-hand particles or right-hand anti-particles. The gauge bosons that serves as mediators for the EW interactions are called charged and neutral weak currents ($W^\pm$, and Z bosons respectively).

1.2 The Higgs mechanism

In the SM the left-handed charged and neutral leptons in each generation transform as an $SU(2)$ doublet, while the right-handed leptons transforms as an $SU(2)$ singlet.

$$E_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad E_R = \bar{e}_R \quad (1.1)$$

Their Lagrangian is required to be invariant under transformations:

$$E_L \rightarrow \exp^{i\left(\alpha^i(x) + \frac{\sigma^i}{2} + \beta(x)/2\right)} E_L, \quad E_R \rightarrow \exp^{i\beta(x)/2} E_R \quad (1.2)$$

With α and β differentiable arbitrary functions and σ^i the Pauli matrices.

The Lagrangian is also required to have mass terms to account for the fact that the charged leptons are known to be massive; the doublet and singlet component would have different quantum numbers, so a term with the form $m\bar{E}_L E_R + h.c$ would violate charge conservation. Instead, in the SM, one can introduce a scalar field ϕ that adds to the Lagrangian terms like $\bar{E}_L \phi E_R + h.c$.

To be able to re-normalise such a field, it is required to have *spin* zero, and to be invariant under $SU(2)$ transformations.

Under $SU(2) \otimes U(1)$ gauge transformations:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^- \end{pmatrix}, \quad \phi \rightarrow \exp^{\alpha^a \sigma^a / 2} \exp^{i\beta/2} \phi \quad (1.3)$$

its covariant derivative would be written as

$$D_\mu \phi = \left(\partial_\mu - i \frac{g}{2} A_\mu^a \sigma^a - \frac{i}{2} g' B_\mu \right) \phi \quad (1.4)$$

With A_μ^a and B_μ corresponding to the $SU(2)$ and $U(1)$ gauge bosons respectively. The most general Lagrangian for this field preserving renormalisability is

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi|^2 + \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2 \quad (1.5)$$

where the coupling to fermions have been ignored. If $\mu^2 > 0$, then the $\phi = 0$ fails to represent a stable vacuum; its minimum is instead a set of points with

$$\langle \phi \rangle = v = \left(\frac{\mu^2}{\lambda} \right)^{1/2} \quad (1.6)$$

this is known as the *vacuum expectation value* of ϕ .

An alternative parametrisation can be chosen

$$\phi = \frac{1}{\sqrt{2}} U(x) \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.7)$$

with $U(x)$ an operator which represents arbitrary $SU(2)$ transformations; this parametrisation allows to chose a convenient gauge where $U(x)$ is equal to one.

The kinetic term of the Higgs Lagrangian (Eq. 1.5) which absorbs terms that take account of ϕ coupling with fields A and B , can be evaluated the scalar field vacuum expectation value (Eq. 1.6)

$$\begin{aligned} \Delta \mathcal{L} &= \frac{1}{2} (0 \ v) \left(\frac{g}{2} A_\mu^a \sigma^a + \frac{1}{2} g' B_\mu \right) \left(\frac{g}{2} A^{b\mu} \sigma^b + \frac{1}{2} g' B^\mu \right) \begin{pmatrix} 0 \\ v \end{pmatrix} \\ &= \frac{1}{2} \frac{v^2}{4} \left[g^2 (A_\mu^1)^2 + g^2 (A_\mu^2)^2 + (-g A_\mu^3 + g' B_\mu)^2 \right] \end{aligned} \quad (1.8)$$

In order to read the massive vector boson as physical particles one can notate mass eigenstates as:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (A_\mu^1 \mp i A_\mu^2) && \text{with mass } m_W = g \frac{v}{2}; \\ Z_\mu^0 &= \frac{1}{\sqrt{g^2 + g'^2}} (g A_\mu^3 - g' B_\mu) && \text{with mass } m_Z = \sqrt{g^2 + g'^2} \frac{v}{2}; \\ A_\mu &= \frac{1}{\sqrt{g^2 + g'^2}} (g' A_\mu^3 + g B_\mu) && \text{with mass } m_A = 0 \end{aligned} \quad (1.9)$$

Chapter 1. Theory introduction

The covariant derivative acting on a fermion field belonging to a general $SU(2)$ representation with $U(1)$ charge Y , can be written in terms of these mass eigenstate fields

$$\begin{aligned} D_\mu &= \partial_\mu - i g A_\mu^a T^a - i g' Y B_\mu \\ &= \partial_\mu - i \frac{g}{\sqrt{2}} \left(W_\mu^+ T^+ + W_\mu^- T^- \right) - i \frac{1}{\sqrt{g^2 + g'^2}} Z_\mu (g^2 T^3 - g'^2 Y) \\ &\quad - i \frac{g g'}{\sqrt{g^2 + g'^2}} A_\mu (T^3 + Y), \end{aligned} \quad (1.10)$$

with $T^\pm = (T^1 \pm i T^2)$ and $T^3 = \frac{\sigma^3}{2}$. One can choose a normalisation so that, in the spinor representation of $SU(2)$, $T^\pm = \frac{1}{2} (\sigma^1 \pm i \sigma^2) = \sigma^\pm$. The electron charge, can be written in terms of the coefficient of the electromagnetic interaction as $e = \frac{g g'}{\sqrt{g^2 + g'^2}}$; and the electric charge quantum number as $Q = T^3 + Y$. Additionally the definition of *weak mixing angle* θ_w (angle that appears in the change of basis from (A^3, B) to (Z^0, A))

$$\begin{pmatrix} Z^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos \theta_w & -\sin \theta_w \\ \sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} A^3 \\ B \end{pmatrix} \quad (1.11)$$

with

$$\cos \theta_w = \frac{g}{\sqrt{g^2 + g'^2}} \quad \text{and} \quad \sin \theta_w = \frac{g'}{\sqrt{g^2 + g'^2}} \quad (1.12)$$

allow one to write Eq. 1.10 as

$$D_\mu = \partial_\mu - i \frac{g}{\sqrt{2}} \left(W_\mu^+ T^+ + W_\mu^- T^- \right) - i \frac{g}{\cos \theta_w} Z_\mu (T^3 - \sin \theta_w Q) - i e A_\mu Q \quad (1.13)$$

The couplings of all the weak boson can be described by two parameters; the e charge and the mixing angle θ_w [8]. From Eqs. 1.9 and 1.10 one can obtain the dependency that exist between the W and Z masses:

$$m_W = m_Z \cos \theta_w \quad (1.14)$$

Including an omitted real-valued term $v \rightarrow v + h(x)$ when ϕ was parametrised, and using expression 1.10; the kinematic term of the Lagrangian in Eq. 1.5 can be then be written as

$$\Delta \mathcal{L}_K = \frac{1}{2} (\partial h)^2 + \left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right] \left(1 + \frac{h}{v} \right)^2 \quad (1.15)$$

This Lagrangian, describes scalar neutral particle h , known as the **Higgs boson**. The strength of the coupling to the W and Z bosons happens to be proportional to their masses.

Out of the $\phi^\dagger \phi$ and $(\phi^\dagger \phi)^2$ terms in Eq. 1.5 one can obtain a mass term for the Higgs, together

with the three-point and four-point self-couplings:

$$\Delta\mathcal{L}_V = -\frac{1}{2}m_H h^2 - m_H \sqrt{\frac{\lambda}{2}} h^3 - \frac{\lambda}{4} h^4, \quad \text{where } m_H = v \sqrt{\frac{\lambda}{2}} \quad (1.16)$$

Similar deductions on a Lagrangian with $\bar{E}_L \phi E_R + h.c$ would also lead to mass terms where the coupling strength will be proportional to the electron, muon, tau and also quark masses.

The coupling of the leptons to the gauge bosons arise from the kinematic term in the Lagrangian:

$$\mathcal{L}_K = \bar{E}_L (i\gamma^\mu D_\mu) E_L + \bar{e}_R (i\gamma^\mu D_\mu) e_R + h.c \quad (1.17)$$

defining $J_Z^\mu = \frac{1}{\cos\theta_w} \left[\frac{\bar{\nu}_L \gamma^\mu \nu_L}{2} + \bar{e}_L \gamma^\mu \left(-\frac{1}{2} + \sin^2\theta_w\right) e_L + \bar{e}_R \gamma^\mu (\sin^2\theta_w) e_R \right]$, $J_\mu^{\mu+} = \frac{1}{\sqrt{2}} (\bar{\nu}_L \gamma^\mu e_L)$, $J_\mu^{\mu-} = \frac{1}{\sqrt{2}} (\bar{e}_L \gamma^\mu \nu_L)$, and $J_{EM}^\mu = -\bar{e} \gamma^\mu e$, the Eq. 1.17 can be written as

$$\begin{aligned} \mathcal{L}_K = & \bar{E}_L (i\gamma^\mu \partial_\mu) E_L + \bar{e}_R (i\gamma^\mu \partial_\mu) e_R + h.c \\ & + g \left(W_\mu^+ J_W^{\mu+} + W_\mu^- J_W^{\mu-} + Z_\mu^0 J_Z^\mu \right) + e A_\mu J_{EM}^\mu \end{aligned} \quad (1.18)$$

Up to here, one have implicitly made the assumption that there is only one ϕ doublet. In reality, there is no reason besides simplicity to make this assumption. Two or more doublets could exist, in such scenarios most of the theoretical arguments still apply. At least one field that transforms as a complex scalar $SU(2)$ doublet is needed. Gauge bosons and fermions acquire their masses from their couplings to the Higgs sector when $SU(2)$ symmetry is spontaneously broken.

Phenomenological consequences are translated into the existence of multiple neutral and charged Higgs bosons. A particularly important model, the Two Higgs Doublet Model (2HDM), assumes the existence of two separate scalar complex doublets: $\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$ and $\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$ with vacuum expectation values $\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$ and $\langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$. When $SU(2)$ symmetry in the 2HDM is broken, five observable Higgs fields are found:

- a light neutral scalar: h^0 ,
- a heavy neutral scalar H^0 ,
- a pseudoscalar A^0 ,
- and two charged Higgs bosons: $H^\pm$

Out of the five Higgs bosons in the 2HDM, only the h^0 and H^0 would couple with the WW and ZZ final states. The definition of a mixing angle α in this neutral sector (h^0 and H^0), and the ratio $\beta = \frac{v_2}{v_1}$ allow to evaluate the coupling behaviour of the Higgs bosons with the weak

Chapter 1. Theory introduction

bosons: $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ scale the VV coupling strengths of h^0 and H^0 respectively, while coupling to quarks and leptons are in general modified by factors involving $\sin \alpha$ and $\cos \alpha$; if the mixing angle tends to one: $\cos \alpha \rightarrow 0$, the $h^0 f \bar{f}$ coupling $\rightarrow 0$, this implies that the light Higgs boson could be fermiophobic.

In terms of elementary particles, the SM provides a very convincing description of the fundamental structure of the observable matter, with bosons serving as mediators in their interactions. In general, it requires only 19 independent and arbitrary input parameters.

- 6 quarks masses, 3 lepton masses,
- 3 gauge couplings (e , θ_w and α_s),
- 3 Cabibbo mixing angles and the CP-violating Kobayashi-Maskawa complex phase,
- the QCD vacuum angle,
- the Higgs boson mass and the vacuum expectation value v .

Experiments have measured with unprecedented precision quantities that confirm accurate predictions of the SM. A typical example is the high order corrections of the electron gyromagnetic ratio. The Dirac equation suggests $g=2$, corrections of this value have been theoretically calculated perturbatively up to order α^4 :

$$\left(\frac{g-2}{2}\right)_{\text{th}} = 0.001159652140(5)(4)(27) \quad (1.19)$$

with experimental evidence showing

$$\left(\frac{g-2}{2}\right)_{\text{exp}} = 0.001159652187(4) \quad (1.20)$$

Although such impressive predictions are seen, experiments have also shown that the SM might need extensions to satisfactorily account for observations. Open questions like the particles mass hierarchy, the absence of right handed neutrino sector, the matter anti-matter asymmetry, the apparent inconsistency of measurement of galaxy masses based on luminosities information and their rotational speeds; could be partially solve in scenarios with a theory beyond the SM.

The most popular of these extensions is the so-called Supersymmetry theory (SUSY) [9–17]. It relates fermions and bosons by introducing one or more operators that turns fermionic states into bosonic states and vice versa. It then predicts the existence of a new set of particles supersymmetric partners of the SM (higgsinos, squarks, sleptons, neutralinos, charginos, gluinos, and goldstinos).

1.3 Quark parton model and Parton Distribution Functions

The quark parton model is one of the fundamental pillars of particle physics. An adequate description of the content of hadrons is crucial for a proper interpretation and prediction of probability amplitudes and in general any physical quantity of any process that involves hadrons.

Using deep inelastic scattering (DIS) data from electron-hadron collisions, it was possible to infer structure functions, as well as describe the properties of the partons inside protons and neutrons. Furthermore, the usage of neutrino beams allowed an important confirmation of the theory, proving the extension of the model and showing the independence of the probe (photons or weak charged currents) that is used. Conserved quantities defined in terms of sum rules and scale invariance/violation would help to parametrise and evaluate the structure functions; in fact, even though DIS does not provide a direct measurement of strong interaction, it was possible to estimate gluon distributions and their evolution based on scale violation principles.

Currently it is known that gluons carry about half of the momentum of a hadron, while the valence and sea quarks carry the second half, also being responsible of carrying the charge of any hadron. The theory is not fully complete yet, indeed several experiments are trying to better understand the nature of the spin of protons and neutrons. It is also an open question in particle physics.

Parametrisation and evolution equations through χ^2 fits on more than 3000 data points across a wide phase space allowed the definition of parton distribution functions (PDFs). Data from many experiments/collaborations are used; this includes DIS data from SLAC, BCDMS, NMC, E665, CCFR, H1, ZEUS, NuTeV, CHORUS,...; Drell-Yan data from E605, E772, E866,..., and recently high E_T jets, Z boson rapidity and W boson asymmetry constraints from CDF and DØ Tevatron's run I and II [18].

Different Collaborations approach the PDF puzzle in different ways. Diverse assumptions and procedures yield to different results. Treatments of important aspects like alpha strong α_s or uncertainties estimations are the main concerns for hadron-hadron experiments where data is still extensively analysed; like in the Tevatron and the LHC where, in many cases, PDFs are (and will be) one of the largest sources of uncertainty. These uncertainties would definitely play an important role on Higgs boson searches where the main production mechanism is initiated by gluons from unexplored regions of the energy scale and parton momentum fraction.

1.3.1 Deep Inelastic Scattering and the Structure Functions

The usage of EW interactions from leptons as probe in lepton-hadron collisions is the simplest mechanism to disentangle the structure of hadrons.

Consider an electron that scatters from an atomic target by exchanging a photon (see Fig. 1.2).

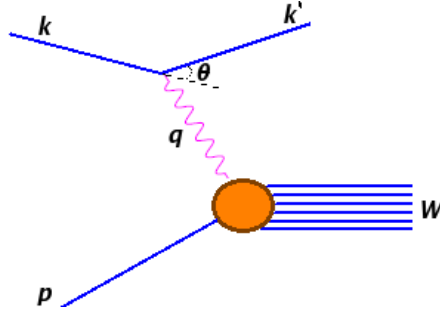


Figure 1.2: Electron scattering by the exchange of one photon.

The target will react differently depending on the amount of energy carried by the virtual photon: it can elastically recoil, it can become excited or it can break up.

The energy transfer is defined as $\nu \equiv E - E'$ where E and E' are the initial and final state electron energies. It can also be written as the invariant mass of the virtual photon (squared four-momenta)

$$q^2 = (k - k')^2 \simeq -2EE'(1 - \cos\theta) = -4EE' \sin^2\left(\frac{1}{2}\theta\right) \quad \text{when } E \text{ and } E' \text{ are } \gg m_e \quad (1.21)$$

the target would be “excited” into a state with mass W :

$$W^2 \equiv (p + q)^2 = p^2 + 2pq + q^2 \quad (1.22)$$

defining $Q^2 = -q^2$ and with $p^2 = M^2$ (since the target is at rest), and $p \cdot q = M\nu$

$$W^2 = M^2 + 2M\nu - Q^2. \quad (1.23)$$

At $Q^2 \approx 0.1 \text{ GeV}^2$ the electron is able to resolve the internal structure of a nucleus, but protons are still seen as point-like objects; for higher Q^2 of the order of $\sim 1 \text{ GeV}^2$ the *form factor* of the protons starts to become evident.

If the coordinate frame of the target is viewed as a system with a very large momentum along the z -axis (much larger than its mass), the four-momenta of the target can be written as:

$$p^\mu = (E; p_T, pz) \quad (1.24)$$

conventionally the P_T of the parton can be neglected, as well as its mass, then it can assume that the linear momentum of the parton is:

$$p = x p_z \quad (1.25)$$

where x is the momentum fraction carried by the parton.

1.3. Quark parton model and Parton Distribution Functions

The parton's momentum is usually expressed in terms of $f_i(x)$, the probability of finding a parton i carrying a momentum fraction x . The total cross-section for electron scattering from the cloud of partons would be the addition of these individual contributions

$$\frac{d^2\sigma}{dQ^2 d\nu} = \sum_i \int dx f_i(x) \left(\frac{d^2\sigma}{dQ^2 d\nu} \right)_i, \quad (1.26)$$

experimentally it is possible to measure the left side of this equation, and it is usually divided in two contributions [19]: W_1 and W_2 .

$$\frac{d^2\sigma}{dQ^2 d\nu} = \frac{4\pi\alpha_s^2}{Q^4} \frac{E'}{E} \left[\cos^2(\tfrac{1}{2}\theta) W_2(\nu, Q^2) + 2 \sin^2(\tfrac{1}{2}\theta) W_1(\nu, Q^2) \right], \quad (1.27)$$

these two *structure functions* control both the angular dependence and the magnitude of the cross-section.

From Eq. 1.22 and by the definition of x , one can conveniently rewrite the functions describing the structure in terms of x . Here it is important to address the so called Bjorken scaling limit [19] where, at $Q^2 \rightarrow \infty$ and $\nu \rightarrow \infty$, the Q^2/ν ratio is finite

$$\begin{aligned} \nu W_2(\nu, Q^2) &\rightarrow F_2(x \equiv Q^2/2M\nu) = \sum_i e_i^2 x f_i(x) \\ MW_1(\nu, Q^2) &\rightarrow F_1(x \equiv Q^2/2M\nu) = F_2(x)/2x. \end{aligned} \quad (1.28)$$

A conventional quantity measurable in the laboratory is the ratio of the longitudinal and transverse cross-sections:

$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{W_2}{W_1} \left(1 + \frac{\nu^2}{Q^2} \right) - 1. \quad (1.29)$$

For the case of spin zero particles, where $W_1 = 0$, $\sigma_L/\sigma_T \rightarrow \infty$. For spin 1/2 parton the Callan-Gross relation is satisfied ($F_2 \simeq 2xF_1$) and $\sigma_L/\sigma_T \xrightarrow{Q^2 \rightarrow \infty} 0$ [20].

The ratio defined in Eq. 1.29 in general depends of $R = R(Q^2, \nu)$, and can be considered as a structure function; indeed it can be related to the longitudinal structure function $F_L(Q^2, \nu) = F_2(Q^2, \nu) - 2xF_1(Q^2, \nu)$. Usually instead of F_1 and F_2 , R and F_2 are commonly used to described the proton. In order to measure R a scan over the beam energy is needed.

Similar formalisms also apply for neutrino-hadron scattering. In this case the exchange of weak currents would suppress the pure elastic scattering contribution leaving place to the quasi-elastic process: $\nu_\mu n \rightarrow \mu^- p$. Experimentally one of the main difficulties is that the incoming ν_μ beam energy is not well determined, but it can be inferred from the scattered lepton and the final state of the hadronic system.

Similar to electron or muon scattering, neutrino scattering involves spins in a similar way, but

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with the advantage that weak currents can distinguish quarks and anti-quarks due to the V-A interaction (see Fig. 1.3). An additional structure function F_3 is introduced to take care of this parity violating component.

In neutrino scattering, from a diagram similar to Fig. 1.2, it is possible to define the angular parameter y :

$$\cos^2 \frac{1}{2} \theta = 1 - y \quad (1.30)$$

this would help to explicitly separate quark anti-quark contribution as seen in Fig. 1.3.

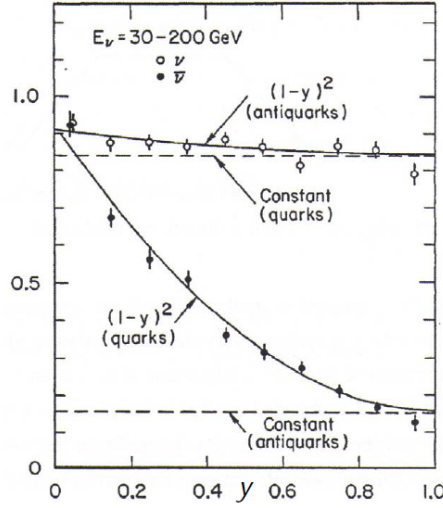


Figure 1.3: Quark anti-quark distributions for ν and $\bar{\nu}$ scattering [21].

After taking into account parity violation ($\sigma_L \neq \sigma_R$) and considering some other details like W boson polarisations and with the assumption of the Callan-Gross relation ($F_2 \simeq 2xF_1 \rightarrow$ spin 1/2), the final cross-section for a neutrino-nucleon scattering (on an isoscalar target) is:

$$\frac{d^2\sigma}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/m_W^2)^2} \left[\frac{F_2 \pm xF_3}{2} + (1-y)^2 \frac{F_2 \mp xF_3}{2} \right]. \quad (1.31)$$

Keeping in mind the analogy with Eq. 1.28, F_2 and F_3 can be seen

$$\begin{aligned} F_2(x) &= 2 \sum [g_i^2 x f_i(x) + g_j^2 x \bar{f}_j(x)] \\ xF_3(x) &= 2 \sum [g_i^2 x f_i(x) - g_j^2 x \bar{f}_j(x)]; \end{aligned} \quad (1.32)$$

These structure functions for neutrino/anti-neutrino nucleon interactions are, to a first ap-

proximation^{1, 2}

$$\begin{aligned}
 \nu p: & \quad F_2 = 2x[d + s + \bar{u} + \bar{c}] & F_3 = 2x[d + s - \bar{u} - \bar{c}] \\
 \nu n: & \quad F_2 = 2x[u + s + \bar{d} + \bar{c}] & F_3 = 2x[u + s - \bar{d} - \bar{c}] \\
 \bar{\nu} p: & \quad F_2 = 2x[u + c + \bar{d} + \bar{s}] & F_3 = 2x[u + c - \bar{d} - \bar{s}] \\
 \bar{\nu} n: & \quad F_2 = 2x[d + c + \bar{u} + \bar{s}] & F_3 = 2x[c + d - \bar{u} - \bar{s}].
 \end{aligned} \tag{1.33}$$

Since additional flavor families contribute to the *sea* quark components only, i.e. $s = \bar{s}$ and $c = \bar{c}$, in an isoscalar target, the symmetry relations $F_2(\bar{\nu}N) = F_2(\nu N)$ and $F_3(\bar{\nu}N) = F_3(\nu N) - 4x[s - c] \approx 2x[u_V + d_V]$ can be assumed.

This provides an important statement, showing that F_3 would mainly contain *valence* quark distributions. Quantities like the average $\frac{F_3(\nu N) + F_3(\bar{\nu} N)}{2} = 2x[u + d - \bar{u} - \bar{d}] = 2x[u_V + d_V]$ could also lead to clean measurements.

1.3.2 Quark Parton Model

The evidence that supports the idea of point-like particles as constituents of the proton, initially relied on the independence of νW_2 on data from experiments made during the 70s exploring different Q^2 and an extended range of scattering angles, see Fig. 1.4. [22]. The phase space scanned corresponded to a region of x close to 0.25. In addition to this, data also showed that a small size of the ratio R would favour spin 1/2 particles as the main carriers of the proton's charge.³

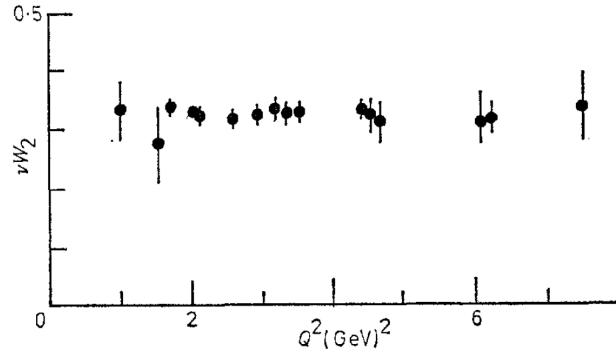


Figure 1.4: Q^2 independence of νW_2 for a fixed x [22].

Various predictions and constraints can be made from integrals over quark densities. These are commonly known as *sum rules*.

¹some quark transitions are favoured by Cabbibo's angle $d \leftrightarrow u, s \leftrightarrow c, \bar{u} \leftrightarrow \bar{d}, \bar{c} \leftrightarrow \bar{s}$

² b contributions have been recently included in some models from CTEQ, MSTW and NNPDF, but they are omitted in this example

³It is still possible to arrange higher spin configurations that also lead to small σ_L/σ_T ratios, but there are good theoretical reasons and constraints to prefer spin 1/2 quarks as the constituent of the proton.

- The conservation of total momentum provides the most basic QCD sum rule. It guarantees that the momentum of the proton is equal to the addition of the momenta of its partons including gluons:

$$\int_0^1 dx(xp) [u + \bar{u} + d + \bar{d} + s + \bar{s}] = p - p_{\text{Gluon}} \quad (1.34)$$

- The Gottfried sum rule constrains neutron and proton quark distributions based on quantum numbers; for instance for protons the quark distributions must satisfy:

$$\begin{aligned} \int_0^1 [u(x) - \bar{u}(x)] dx &= 2 \\ \int_0^1 [d(x) - \bar{d}(x)] dx &= 1 \\ \int_0^1 [s(x) - \bar{s}(x)] dx &= 0 \end{aligned} \quad (1.35)$$

- For neutrino DIS, some other sum rules can be built. The asymmetries of valence quark/anti-quark in proton and neutrons allows the following conservation rule:

$$I_A = \int_0^1 \frac{F_2(\bar{\nu}p) - F_2(\nu p)}{x} dx = \int_0^1 \frac{F_2(\bar{\nu}n) - F_2(\nu p)}{x} dx = \int_0^1 2(u_V - d_V) dx = 2 \quad (1.36)$$

where the V index refers to valence quarks. This is known as the Alder sum rule, and due to its Q^2 independence, it has no QCD corrections.

- The Gross-Llewellyn-Smith sum rule also applies for neutrino DIS and is described in terms of:

$$I_{GLS} = \int_0^1 \frac{x F_3}{x} dx = \int_0^1 (u_V + d_V) dx = 3 \left(1 + \frac{\alpha_s}{\pi} \right) \quad (1.37)$$

Besides imposing Q^2 and $\nu \gg M^2$ the ideas behind the quark-parton model need a large set of non-trivial, but supported assumptions: the factorisation of cross-sections as a calculable part and one that is not, and in particular the extraction of gluon densities as side product of the scaling violation.

The total cross-section is considered to be the incoherent sum of (point-like) scattering cross-sections of the individual partons (charged spin 1/2 = quarks, and neutral spin 1=gluons). The hadronisation process is expected to occur on a much larger time scale, and can be neglected in the determination of a hard scattering cross-section.

After data from different regions of the phase space started to arrive it was possible to see that the structure functions were not really independent of Q^2 (Fig. 1.5 shows the the Q^2 dependence of the structure function F_2 for different values of x).

In QCD, *asymptotic freedom* predicts an energy scale dependence on the strong coupling

1.3. Quark parton model and Parton Distribution Functions

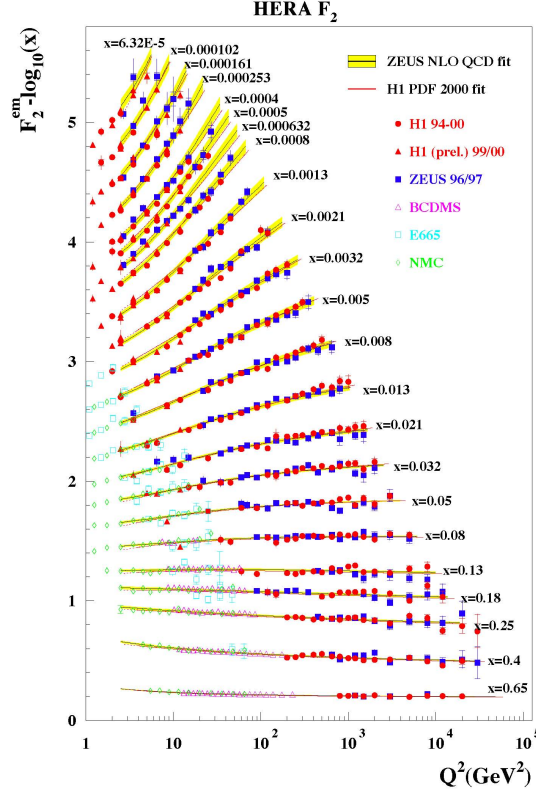


Figure 1.5: Proton structure function for different values of x as function of Q^2 [23].

constant:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + b_0 \alpha_s(\mu^2) \log \frac{Q^2}{\mu^2}} \quad (1.38)$$

With this reasoning it was possible to rewrite the structure functions including corrections from α_s

$$\frac{F_2(x, Q^2)}{x} = \sum_i e_i^2 (f_i(x) + \Delta f_i(x, Q^2)) \quad (1.39)$$

where Δf are corrections due to gluon emission and splitting:

$$\Delta f(x, Q^2) = \frac{\alpha_s}{2\pi} \log\left(\frac{Q^2}{\mu^2}\right) \int_0^1 \frac{dy}{y} [f(y) P_{qq}(x/y) + g(y) P_{qg}(x/y)] \quad (1.40)$$

P_{qg} are called splitting functions, which are analytical QCD expressions that represent the probability of a quark of momentum y emitting a gluon and then becoming a quark with momentum x . In a similar way P_{qq} represent the probability amplitude product of the addition of all possible diagrams that would lead to a 2 quark final state.

In general the dependence of the structure functions in terms of the splitting functions and the α_s evolution can be generalised as:

$$\frac{df_i(x, Q^2, \alpha_s(Q^2))}{d \ln Q^2} = \sum_j P_{ij}(x, \alpha_s(Q^2)) \otimes f_j(x, Q^2, \alpha_s(Q^2)) \quad (1.41)$$

this is the master equation known as Dokshitz-Gribo-Lipatov-Altarelli-Parisi (DGLAP) evolution. It predicts the form of a given parton distribution function for $Q^2 > Q_0^2$. In general kinematic cuts on the data are usually needed. A lower bound on Q^2 guarantees the perturbative QCD is still applicable, cuts on W^2 avoid higher twist terms (usual formalism is first twist order), or cuts on x avoid regions with $\ln \frac{1}{x}$ re-summations and non-linear effects.⁵

1.3.3 Parton Distribution Functions

In practice the problem is reduced to start considering the parton evolution at low scale Q_0 1 GeV² and use a form of Eq. 1.41 to evolve the 11 different parton distributions that matter: $u, \bar{u}, d, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$ plus the gluon. Some constraints can be made if one takes into account that $m_c, m_b \gg \Lambda_{\text{QCD}}$, then heavy parton distributions can be determined perturbatively. This leaves 7 independent combinations⁶ (see Fig. 1.6).

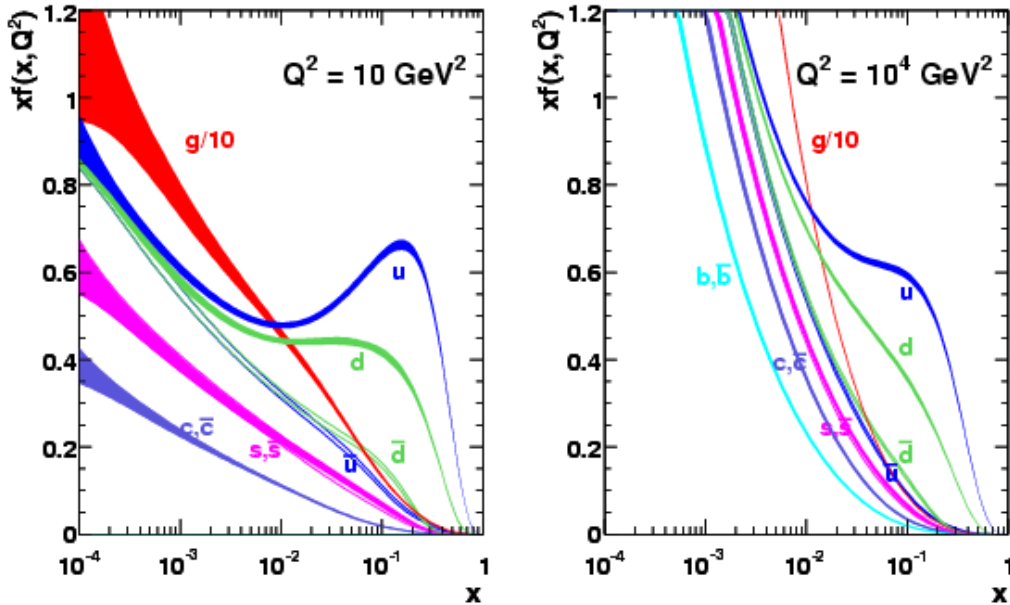


Figure 1.6: Next-to-leading order parton distributions for protons fitted by the MSTW collaboration, for two different Q^2 (MSTW2008 next-to-leading order PDFs (68% CL)) [24].

⁵DGLAP evolution equations have been obtained up to next-to-next-leading order; “The harder the order in perturbation theory, the weaker the scale dependence”

⁶Or 6 if one assumes that sea quarks and sea anti-quarks have same distributions, but this is not a common assumption.

1.3. Quark parton model and Parton Distribution Functions

Many collaborations have developed different approaches to perform the PDF fits. Up to early 2009⁷, the CTEQ, MSTW and the HERA [23] collaborations have fully implemented a general mass-variable flavor number scheme (GM-VFNS), modelling in a more accurate way both regions where $Q^2 \leq \mu^2$ and $Q^2 \gg \mu^2$, including the sum over $\ln^n(Q^2/\mu^2)$ terms and considering $\mathcal{O}(\mu^2/Q^2)$ corrections. This is particularly important for prediction of the evolution in the heavy flavor regime⁸.

Many different parametrisations for the parton densities have been tried. Eq. 1.42 shows the one chosen by the MSTW collaboration, where the left most part takes care of the low- x region, the middle terms the high- x region, and the right most takes care of a proper transition between these two momentum fraction regions:

$$xf_i(x) = A_i x^{\alpha_i} (1-x)^{\beta_i} \left(1 + \epsilon_i \sqrt{x + \gamma_i x}\right). \quad (1.42)$$

CTEQ instead, parametrise their partonic densities as follows:

$$xf_i(x) = A_0 x^{A_1} (1-x)^{A_2} e^{A_3 x} (1 + e^{A_4 x})^{A_5}. \quad (1.43)$$

The parameters A_i are fixed through momentum and sum rules, they are also constrained by model choices. NNPDF uses a much more general form, but all of them converge to a common limit in the range $x \in [0, 1]$.

The common procedure is to minimise χ^2 and define eigenvectors of parameter combinations expanding about a best fit value. The exception for this is the NNPDFs which follows a neural network formalism.

- **MSTW2008** It is formed by 20 eigenvectors, and α_s as well as its uncertainty are determined by the fit. They also produce next-to-leading order (NLO) and next-to-next-leading order (NNLO) PDF sets. Uncertainties intrinsically include the determinations of the coupling constant, this has been controversial; as well as the usage of 68% CL error sets instead of 90% CL. In the most recent version, a full set of PDFs was produced using different priors for α_s as well as both error set 68 and 90% CL. Its $\Delta\chi^2$ ranges from 5 to 20 [24].
- **CTEQ6.6** Considers 22 eigenvectors, uses the global average value for α_s at the Z pole ($\alpha_s(m_Z) = 0.1184 \pm 0.0007$) and remarks a very weak correlation between PDFs and the coupling constant suggesting to add them in quadrature. In their last versions some side values of α_s for comparison purposes were also provided. CTEQ supplies fits at leading order (LO) and NLO and their $\Delta\chi^2$ reaches up to 50 (1 sigma).

⁷The PDF sets have been extensively updated with a much more complete and compressive set of calculation during the last year, nevertheless most of the Monte Carlo studies describe in this document where based on the versions of PDFs described here.

⁸As example, the GM-VFNS can lead to differences on small- x quarks up to 8% at the electroweak scale when comparing with a zero mass-variable flavor number scheme

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- **NNPDF2.0** As neural network PDFs uses a Monte Carlo MC method for uncertainty estimations, as CTEQ uses the global average of α_s and $\Delta\alpha_s$ is modelled as a Gaussian variable which is determined by spread of replicas; a direct relation to $\Delta\chi^2$ in global fit is not trivial. LO, NLO and NNLO PDFs are currently being produced.
- **HERAPDF2.0** Has 9 eigenvectors, it built additional model for parametrisation uncertainties, and provides PDFs at LO and NLO.
- **ABKM09** Provides 21 parton parameters $\Delta\chi^2 = 1$ while **GJR08** has 12 parton parameters and $\Delta\chi^2 \approx 1$ imposing strong theory constraints on their models. Both of the Collaborations provided PDFs up to NNLO.

The data-sets used are not always the same either; two of these collaborations, CTEQ and MSTW have recently updated their results using recent Tevatron's data, while some others like the H1-ZEUS collaborations prefer to use only electron-proton data from HERA:

- **MSTW2008** Fit all previous types of data. Including most up-to-date Tevatron jet data, but not the most recent HERA combination of data.
- **CTEQ6.6** Very similar to MSTW, but not quite as up-to-date on Tevatron data.
- **NNPDF2.0** Includes all above except HERA jet data (which is not the strongest constraint) and heavy flavour structure functions. Include HERA combined data.
- **HERAPDF2.0** is based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data.
- **ABKM09** Fit to DIS and fix target Drell-Yan data. **GJR08** uses similar data, plus Tevatron's jet data.

Parton Distribution Functions Uncertainties

The Parton Distribution Functions uncertainties have typically been determined by allowing excursions from the best fit parameters that result in increases in the total χ^2 values within a pre-determined range. This range is difficult to determine from a rigorous statistical basis, given the wide range of processes and data included in the global fits, and tends to be a matter of choice on the part of the global fitting groups. In the past, $\Delta\chi^2$ has been on the order of 50 (MSTW) or 100 (CTEQ) for a 90% CL, rather than the canonical value of $\Delta\chi^2$ of 1 for a 1- σ uncertainty and 2.7 for a 90% confidence level (CL)⁹. Thus, PDF uncertainties for CTEQ have tended to be larger than those determined from MSTW¹⁰. Both groups have recently been

⁹Some recent studies have indicated that the need for a larger $\Delta\chi^2$ can be tied to parameterization biases inherent in the global fits as well as to conflicting data sets used in the fits.

¹⁰CTEQ (and the NNPDF collaboration) uses the correlated systematic error information for all experiments for which this information is available; MSTW uses the correlated information only for the Tevatron jet experiments (and the Z rapidity distribution) and adds all other experimental systematic errors in quadrature with the statistical error.

developing more sophisticated treatments for the determination of the error PDFs, and the size of the uncertainties for CTEQ6.6 and MSTW2008 are closer than with previous generations of PDFs from the two groups. PDF uncertainties corresponding to a 68% CL limit (1-sigma) can be approximately calculated by the appropriate scaling of the 90% CL errors. The MSTW2008 PDFs have specific error PDFs corresponding to a 68% CL in addition to those corresponding to 90% CL. The approximations involved can be observed in comparing cross-section uncertainties using both sets of error PDFs; in many cases, the scaling between them is larger than the factor of 1.6 expected from statistical considerations.

A large number of parameters are needed in order to fully specify the behaviour of each flavor of PDF over the full x -range (Eqs. 1.42 and 1.43). Some parameters can be fixed at reasonable values while others can be determined from sum rules: the net result is that the CTEQ6.6 (CT09) PDFs have 22 (24) free parameters, while the MSTW2008 PDFs have 20 free parameters. Typically, error PDFs are determined by diagonalising the Hessian matrix corresponding to the free fit parameters (22×22 for CTEQ6.6). The resulting eigenvectors form an orthonormal basis set from which the uncertainty for any cross-section can be determined using the *Master Equation*:

$$\begin{aligned}\Delta X_{max}^+ &= \sqrt{\sum_{i=1}^N [\max(X_i^+ - X_0, X_i^- - X_0, 0)]^2} \\ \Delta X_{max}^- &= \sqrt{\sum_{i=1}^N [\max(X_0 - X_i^+, X_0 - X_i^-, 0)]^2}\end{aligned}\tag{1.44}$$

ΔX^+ adds in quadrature the PDF error contributions that lead to an increase in the observable X and ΔX^- the PDF error contributions that lead to a decrease. The addition in quadrature is justified by the eigenvectors forming an orthonormal basis. The sum is over all N eigenvector directions, or 22(24) in the case of CTEQ6.6(CT09). Ordinarily, $X_i^+ - X_0$ will be positive and $X_i^- - X_0$ will be negative, and thus it is trivial as to which term is to be included in each quadratic sum. For the higher number eigenvectors, however, we have seen that the “+” and “-” contributions may be in the same direction. In this case, only the most positive term will be included in the calculation of ΔX^+ and the most negative in the calculation of ΔX^- . Thus, there may be less than N terms for either the “+” or “-” directions.

Alternatively, the PDF uncertainty can be calculated using the symmetric prescription [25]:

$$\Delta X = \frac{1}{2} \sqrt{\sum_{i=1}^N [X_i^+ - X_i^-]^2}\tag{1.45}$$

However, the net result should be very similar to that of the asymmetric form above for most

calculations.

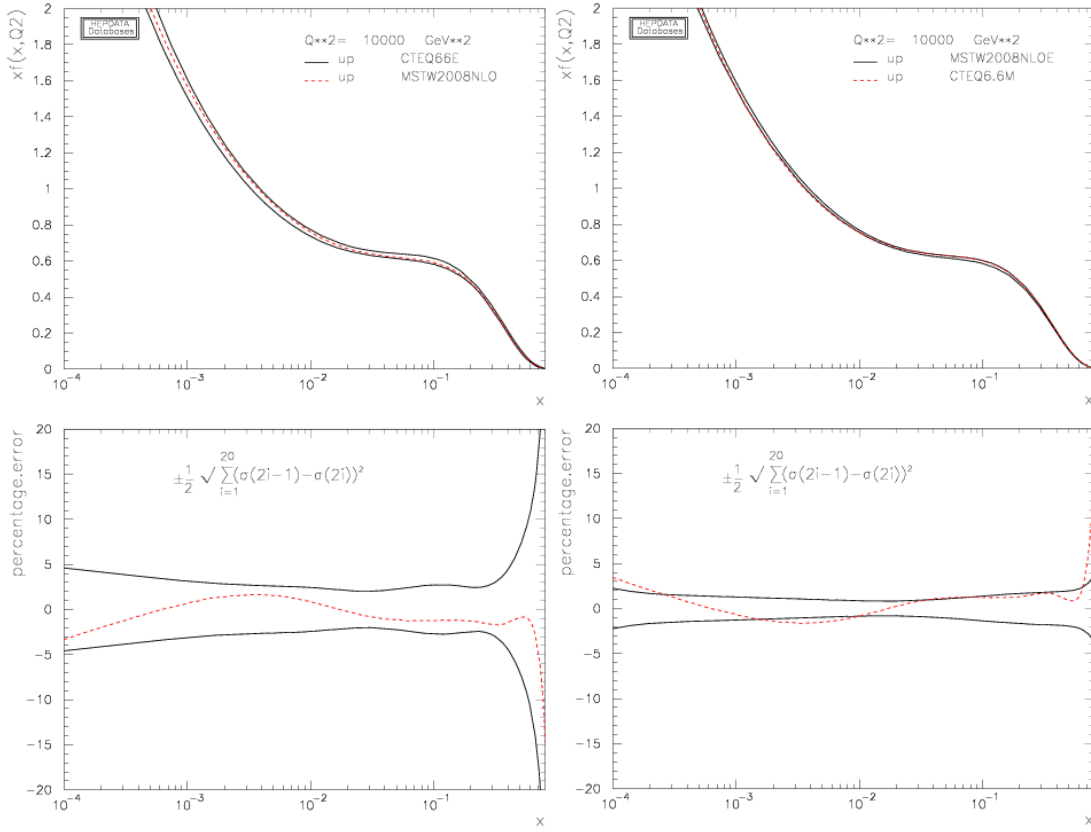


Figure 1.7: A comparison of the u -quark distributions from the CTQE6.6 and the MSTW2008 PDF sets, at a Q^2 value of 10^4 GeV^2 . On the left the u quark distribution from MSTW2008 is compared to the PDF error band from CTEQ6.6; the reverse is plotted on the right. The CTEQ6.6 uncertainty band corresponds to the 90% CL, while the MSTW2008 uncertainty band corresponds to the 68% CL.

Consider the example of Higgs boson production through gg fusion at the designed centre-of-mass energy of 14 TeV. The most important contributions to the uncertainty in the cross-section for a mass of 120 GeV would come from (within the CTEQ6.6 PDF set) eigenvectors 4, 6, 11 and 16. These eigenvectors continue to be important for Higgs boson masses between 200 and 300 GeV, but other eigenvectors become important as well, especially at 300 GeV (5 and 7).

In Fig. 1.7 (left), the up quark distribution for MSTW2008 (at a Q^2 value of 10^4 GeV^2) is compared to the uncertainty on the up quark distribution for CTEQ6.6; on the right, the CTEQ6.6 up quark distribution is compared to the up quark uncertainty for MSTW2008. In Fig. 1.8 (left), the gluon distribution for MSTW2008 (at a Q^2 value of 10^4 GeV^2) is compared to the uncertainty on the gluon distribution for CTEQ6.6; on the right, the CTEQ6.6 gluon distribution is compared to the up quark uncertainty for MSTW2008. For both figures, the CTEQ6.6 PDF uncertainty

1.3. Quark parton model and Parton Distribution Functions

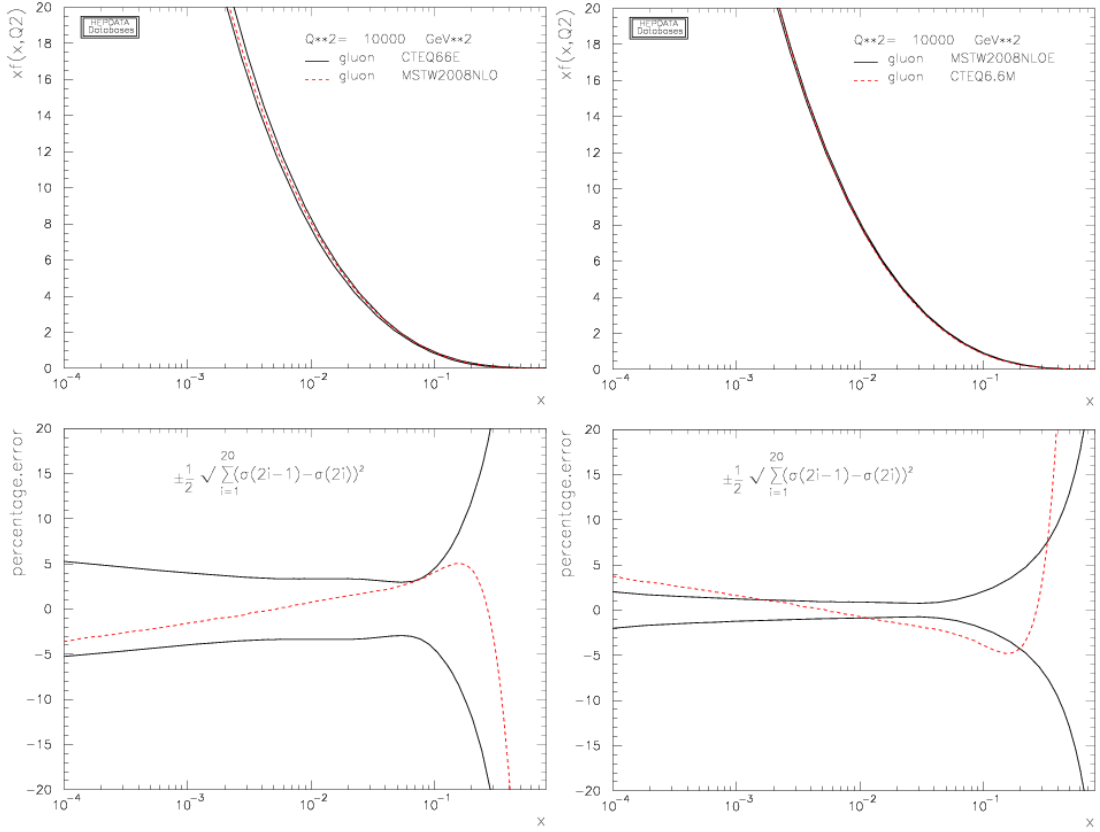


Figure 1.8: A comparison of the gluon distributions from the CTEQ6.6 and the MSTW2008 PDF sets, at a Q^2 value of 10^4 GeV^2 . On the left the gluon distribution from MSTW2008 is compared to the PDF error band from CTEQ6.6; the reverse is plotted on the right. The CTEQ6.6 uncertainty band corresponds to the 90% CL, while the MSTW2008 uncertainty band corresponds to the 68% CL.

is for 90% CL, while the MSTW2008 uncertainty is for 68% CL. It can be seen that the PDF uncertainties (at the 90% CL) are about 5% for the relevant PDFs over the range of interest for electroweak and Higgs bosons production at the LHC. It is also evident from the plots that the MSTW2008 PDFs lie within the CTEQ6.6 (90% CL) PDF error bands; the CTEQ6.6 PDFs are sometimes outside the MSTW2008 PDF error bands. If the central values of competing PDFs do not lay within the error bands of each other, this may be an indication of a basic disagreement or difficulty which needs be understood.

As example of alternative formalisms, the Neural Net PDF Collaboration obtains its uncertainties by tossing toy Monte Carlo. Many replicas of the data are created, obtaining PDF instances in each case by fitting to a trained set and comparing it to a validation set [26]. The v.2 of NNPDF, used the zero mass variable flavor number scheme (ZM-VFNS). In some specific cases, produced results that were a bit off compared to the ones obtained with CTEQ or MSTW, but the major part of the community agrees that NNPDF formalisms in particular for uncertainties

estimation can be more convenient and robust than others.

PDFs and Processes at the LHC

At the LHC observables can be precisely measured. Even though electroweak processes are overwhelmed by QCD backgrounds, the large luminosities allow very low statistical errors. Elaborate detector and physics models plus data-driven background subtractions also provide low experimental systematic uncertainties; all these, plus a compromise of observables “free” of new physics are the main requirements to produce data that would constrain the next generation of PDFs.

The most common constraints on PDFs are coming from electroweak and QCD shapes as well as cross-sections ratios or even direct fits on the PDFs. At the centre-of-mass energy that the

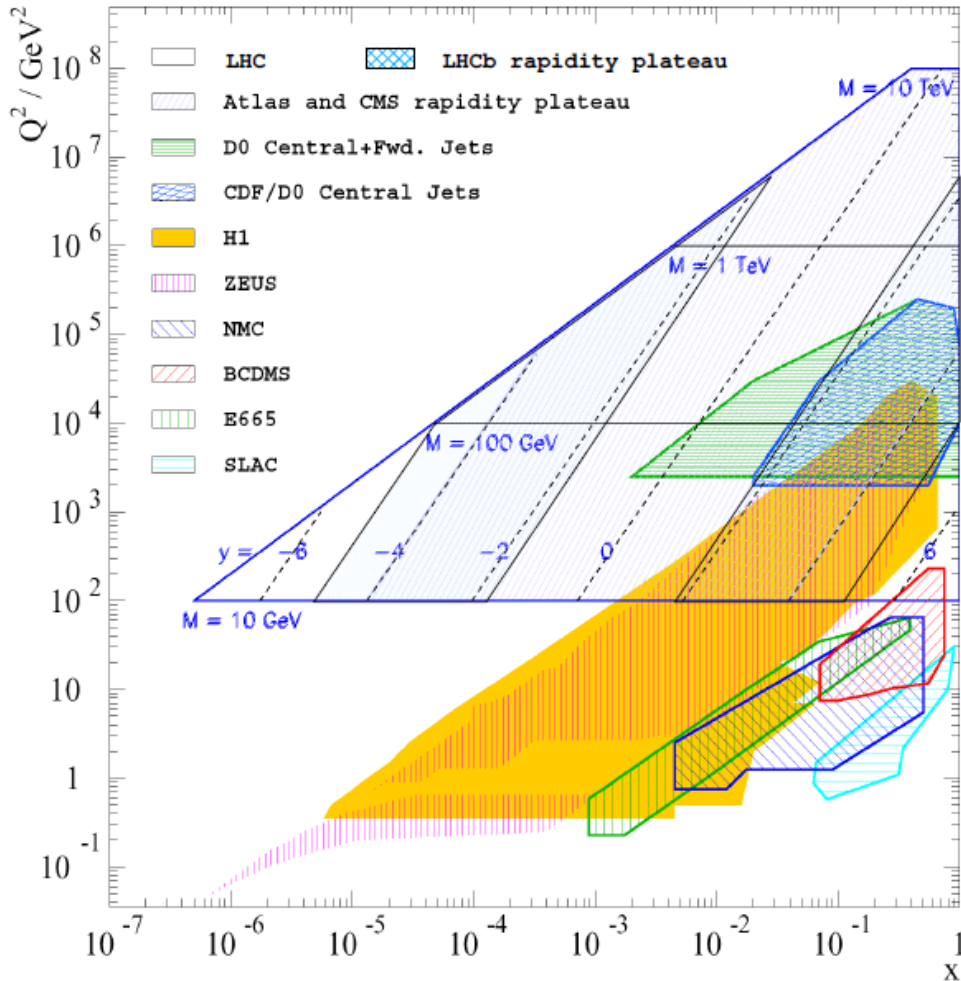


Figure 1.9: Q^2 and x regions that are expected to be explored by the LHC at its designed centre-of-mass energy [27].

1.3. Quark parton model and Parton Distribution Functions

LHC is operating (and even more at the $\sqrt{s}$ it will operate), the quark, anti-quark and gluon distributions are being tested in previously unexplored ranges of Q^2 , larger than 10^7 and very low momentum fractions, from 0.1 up to 0.0001 (see Fig. 1.9).

The fact of having significant amounts of data at $\sqrt{s} < 14$ TeV, 7 TeV for 2010-2011 and possibly some 8 TeV later, will allow the connection among regions already swept by many other experiments like the Tevatron.

Jet production at the LHC provide important constraints to the parton distribution functions; this is supported by the large statistics of high P_T jets ($d\sigma/\sigma \approx 1\%$ for 2 TeV having $\int \mathcal{L} dt = 100 \text{ fb}^{-1}$ with $\sqrt{s} = 14$ TeV) and the extended sensitivity in forward regions ($|\eta|$ up to 4.8). It is extremely important to have under control non diffractive minimum bias and underlying events, as well as the development of techniques to precisely calibrate jet at the TeV scale.

γ +jets production is a relatively clean physics process with a huge cross-section; $q\bar{q}/qg \rightarrow \gamma + \text{jets}$, and $gg \rightarrow \gamma\gamma + X$ through a quark-box are processes that involve small backgrounds. Electromagnetic calibration is in general better understood and in principle provides smaller systematic errors.

Heavy flavor production is also an ideal scenario to test partonic luminosities. Unfortunately a very precise understanding of c and b jet discriminators is needed. Often, systematics associated with heavy flavor taggers, as well as contamination from light flavor make it a very challenging analysis.

Motivations to use charged vector boson data to constrain PDFs are based on the small theoretical errors and small levels of background contamination. At the LHC, ud and cs constraints can be obtained by $W^\pm$ boson production studies.

The production of W boson is known at NNLO and the largest uncertainty comes from PDFs (4-7%). The contributing region of momentum fraction varies between 5×10^{-4} to 5×10^{-2} .

Due to the valence quark charge, distributions in protons (and anti-protons), W^- and W^+ are asymmetrically produced. A commonly used quantity to characterise this difference is defined as:

$$A = \frac{\frac{d\sigma}{d\eta_{\ell^+}} - \frac{d\sigma}{d\eta_{\ell^-}}}{\frac{d\sigma}{d\eta_{\ell^+}} + \frac{d\sigma}{d\eta_{\ell^-}}} \approx \frac{u_V - d_V}{u_V + d_V + 2q_{\text{sea}}} \quad \text{at LO.} \quad (1.46)$$

In Fig. 1.10 it is shown how the reconstructed asymmetry does not overlap for some of the PDF fits. This is particularly evident for large rapidity values.

Unfortunately some other interesting quantities like $\frac{d\sigma}{dP_T^W}$ are not directly accessible due the neutrino presence in the final state. A very precise measurement on the missing transverse energy would be necessary. The charged leptonic decay of the Z boson is one of the cleanest signatures measured at the LHC detectors. The clear resonance and the direct access to

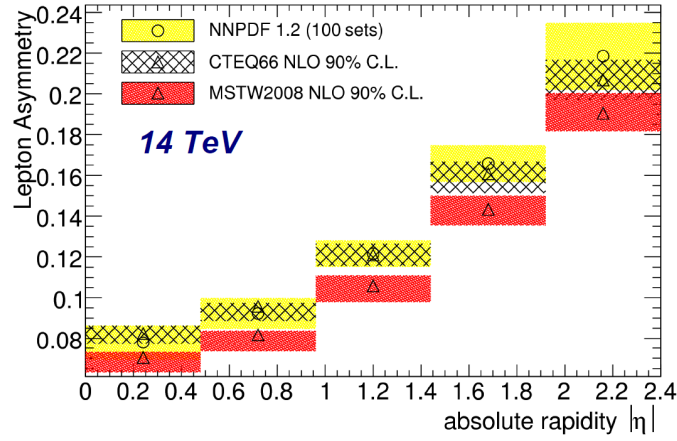


Figure 1.10: Pythia W charge asymmetry errors for different PDF sets [27].

quantities like transverse momentum allows a mapping of low- x regions of gluons and sea quarks as well as constraints on non-perturbative soft gluon radiation models.

At the experimental level it is crucial to understand lepton efficiencies and in general the

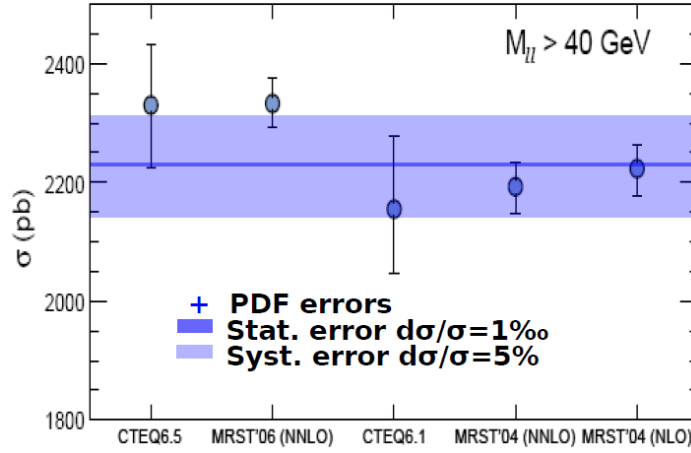


Figure 1.11: Z boson cross-section estimations with different PDF sets at the LHC [27].

uncertainties related with the selection acceptance. Figure 1.11 shows the NLO prediction for Z boson production with different PDF sets.

A powerful way to reduce experimental systematic uncertainties especially those arising from overall normalisations like the luminosity, is the usage of ratios. W and Z boson measurements are led by similar lepton selection, isolation and shower shapes, as well as P_T and other kinematic requirements; indeed a common trigger can be used in both cases, as result, close regions from phase space are shared.

Impact of PDFs on Higgs boson searches

Gluons carry the largest uncertainties due to the fact that gluon distributions inside hadrons are obtained mostly from indirect methods like sum rules and scaling violation.

In addition, from the perturbation theory point of view the gluon-gluon fusion process has a very slow convergence, where a high order (HO) correction could change the cross-section by up to 70% compared to the LO cross-section. In Chap. 2 some more details about HO contributions are given.

For a given amount of data, the final interpretation in order to claim discovery or exclusion of the SM Higgs boson strongly depends on the cross-section hypothesis value as well as the uncertainty predicted by the theory. Unfortunately this normalisation fluctuates significantly depending on the PDF input and the respective value given to constants and parameters like the heavy quark masses or the strong coupling constant. For example, Figure 1.12 illustrates the different cross-section values for the SM Higgs boson ($m_H=120$ GeV and $\sqrt{s}=7$ TeV), when different PDFs with their respective α_s preference are used as input. It is often instructive

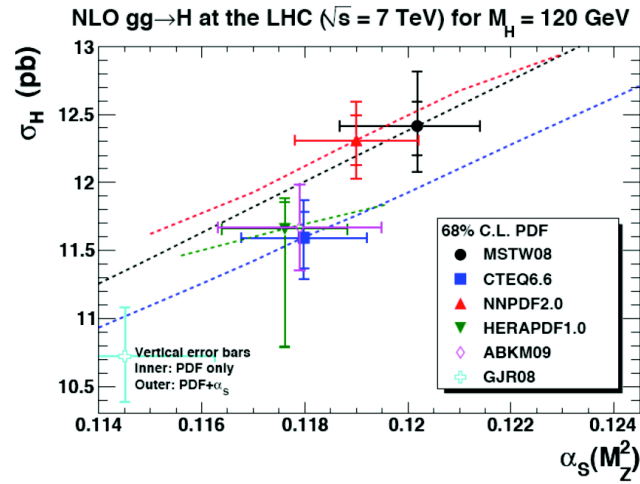


Figure 1.12: NLO Higgs boson cross-section predictions for various PDF sets and the respective α_s used by the different fitting groups [28].

to determine whether a particular collider observable shares common degrees of freedom with another collider cross-section through the non-perturbative PDF parametrisation. Such correlations can be useful in providing ratios of cross-sections that have smaller theoretical uncertainties than either cross-section by itself. A quantity, $\cos\varphi$ (the correlation cosine), can be calculated that represents the degree to which two cross-sections are correlated, a value of this quantity near 1 implies a very strong correlation, near zero, no correlation, and near -1 , a very strong anti-correlation [25], as illustrated in Fig. 1.13. Here φ represents the angle between the gradient vectors of the two cross-sections in the Hessian eigenvector space, and

Chapter 1. Theory introduction

can be calculated as shown in the equation below (for two cross-sections X and Y) ¹¹:

$$\cos \varphi = \frac{\vec{\nabla} X \cdot \vec{\nabla} Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^N \left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right). \quad (1.47)$$

Thus, $\cos \varphi$ can easily be defined with the knowledge of the cross-sections for X and Y for each of the Hessian eigenvectors. For example, one would expect (and find) the W and Z

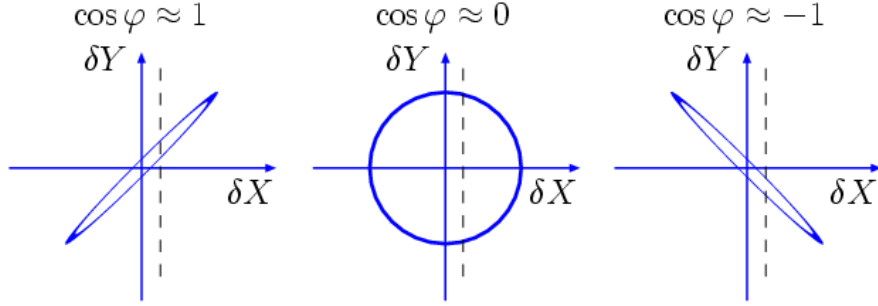


Figure 1.13: Dependence on the correlation ellipse formed in the $\delta X - \delta Y$ plane on the value of $\cos \varphi$. [25].

cross-sections to be very strongly correlated, as both are produced by similar initial states in the same x range. A plot of the correlation cosines for various processes is shown in Fig. 1.14. It can be observed, for example, for Higgs boson production through gg fusion, the process goes from a mild correlation at low Higgs boson mass (120 GeV) with the W cross-section at the LHC, to a very strong anti-correlation for high Higgs boson masses (500 GeV). Conversely, the correlation of the Higgs boson cross-section with respect to the $t\bar{t}$ cross-section is the mirror image of that to the W cross-section.

¹¹More generally, it can be defined in terms of the correlation between two quantities; it does not require the use of the Hessian technique.

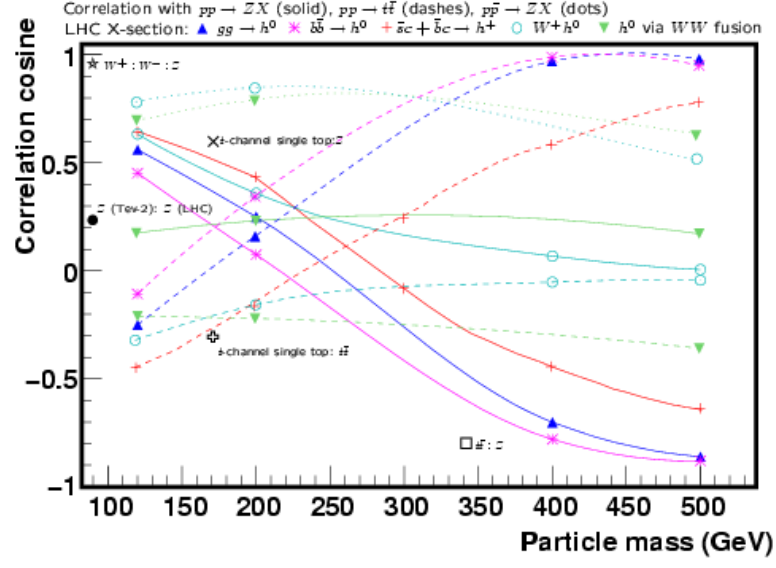


Figure 1.14: The correlation $\cos \varphi$ for Higgs boson searches at the LHC with respect to Z boson production at the LHC (solid) and Tevatron (dots), and $t\bar{t}$ production at the LHC (dashes), plotted as a function of Higgs boson mass. Separate markers denote correlations of W , t -channel single-top cross-sections at the LHC and Z cross-section at the Tevatron with respect to Z and $t\bar{t}$ cross-sections at the LHC [25].

2 Standard Model Higgs boson production



"Higgs mechanism should be renamed the 'ABEGHHK'tH mechanism'"

Peter Higgs boson

This chapter summarises the state-of-the-art calculations on the production and decay of the Higgs boson particle. High order corrections are needed to correctly analyse and interpret the observed data. At the LHC the relevant production mechanisms are the gluon-gluon fusion through a top quark loop, the fusion of vector bosons produced on vertexes at the incoming quarks, and also the so-called associated production which can be seen as Higgs boson being radiated from a weak current.

Finally it summarises the current state of constraints given by direct and indirect searches of the Higgs boson.

2.1 Production mechanisms

At the LHC, the SM Higgs boson can be produced through four main mechanisms. Due to the large gluon luminosities expected in the high energy beams of proton-proton collisions, the fusion of gluons through a loop of heavy quarks is the dominant production process. It is followed by the vector boson fusion (VBF) process, in which the emission of virtual bosons from incoming partons produces a Higgs boson particle; in this mechanism the presence of the two scattered quarks ending in the forward rapidity region can provide a peculiar signature which can be exploited to discriminate from background processes. Although suppressed in $p-p$ colliders¹, the production in association with a W or a Z boson becomes relevant in the region of a low Higgs boson mass hypothesis. The typically high transverse momentum (P_T) leptonic signatures of the decay of the weak bosons can be used to trigger and discriminate from overwhelming multi-jet background and simultaneously profit out of the large decay

¹As opposite to the Tevatron's $p-\bar{p}$ collider in which the presence of valence quarks and anti-quarks enhance the Higgs boson production in association with vector bosons

branching ratio (BR) of the Higgs bosons going into a pair of heavy flavour quarks. Finally, in the case of a very low mass Higgs boson search, the production of a Higgs boson together with a top quark pair can be also used. The analyses documented on this thesis profit of the two most important mechanisms gluon fusion and VBF.

For the prospect studies that aimed the designed and construction of the LHC and its experiments, the community used cross-section values for Higgs boson production estimated up to NLO assuming a beam energy of $\sqrt{s} = 14$ TeV. This calculations were based on the HIGLU, vv2H and v2HV codes [29].

After the LHC incident back in September 2008 [7], a decision to run the LHC using a substantially smaller beam energy was taken. At the time, it was not known which was going to be the running parameters of the LHC. A new common and consistent set of cross-section estimations were needed by the analysers. The three following subsection on this chapter collect some details of the estimations done assuming different centre-of-mass energy for a wide Higgs boson mass range using NLO estimations (which were the best known calculations available at that time). These estimations were later used to scale down previous studies performed at $\sqrt{s} = 14$ TeV, helping the accelerator team to find the optimal physics motivated conditions under which the machine could run without compromising the health and reliability of the LHC ².

2.1.1 Gluon-gluon fusion

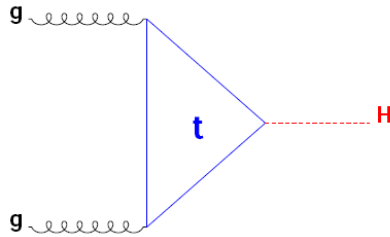


Figure 2.1: Leading Order Feynman diagram for gluon-gluon fusion SM Higgs boson production through a top quark loop.

The LO Feynman diagram for gluon-gluon fusion Higgs boson production can be seen in Fig. 2.1. As gluons are driven by strong interactions, QCD radiative corrections are needed to accurately obtain theoretical predictions. The LO diagram is proportional to α_s^2 . In the quark loop, the top-quark is expected to be dominant due to its large Yukawa coupling to the Higgs boson, with a mild contribution of b -quark. Next-to-leading order calculations showed an increase of more than 100% with respect to LO, with a clear dependency on the m_H hypothesis as well as the $\sqrt{s}$. Different calculations [29–31] showed that for a Higgs boson mass

²A website was prepared at the time collecting some of this information:
<http://montoya.web.cern.ch/montoya/xsections/text.html>

(m_H) smaller than 300 GeV, the effective theory in which the quark loop is shrunk to a point assuming $m_{top} \rightarrow \infty$ is at the percent level agreement with respect to the full calculation. This became important later when due to its complexity, next-to-next-to-leading order (NNLO) calculations were made possible only based on this assumption.

Cross-sections for the gluon-gluon fusion process estimated with the HIGLU code and the corresponding LO or NLO CTEQ6X PDF are shown in Fig. 2.3. The input parameters used are summarised in Tab. 2.1 As explained in Chap. 1, the choice of α_s is an important parameter which eventually needs to be in concordance with the set configured on the PDF set. The choice set here was based on the world average value suggested by the CTEQ collaboration at the time that these calculations were obtained.

Table 2.1: Input Parameters for σ_H estimations at LO and NLO

LO				NLO			
$\Lambda_{\text{QCD}}^{\text{LO}}$ [MeV]		165		$\Lambda_{\text{QCD}}^{\text{NLO}}$ [MeV]		226	
$\alpha_s^{\text{LO}}(m_Z)$		0.130		$\alpha_s^{\text{NLO}}(m_Z)$		0.118	
m_{uds} [MeV]	190	m_c [GeV]	1.4	m_b [GeV]	4.60	m_t [GeV]	172
m_Z [GeV]	91.187	m_W [GeV]	80.41	G_F	1.16639×10^{-5}	N_F	5

In Fig. 2.2 it is shown the k -factors of the first QCD HO correction when compared to the LO calculation ($k\text{-factor} = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}}$) for different centre-of-mass energies. For a m_H hypothesis of 130 GeV, the NLO correction at $\sqrt{s} = 14$ TeV would add a $79 \pm 2\%$ on the top of the LO, while at $\sqrt{s} = 7$ TeV the addition is of about $89 \pm 2\%$

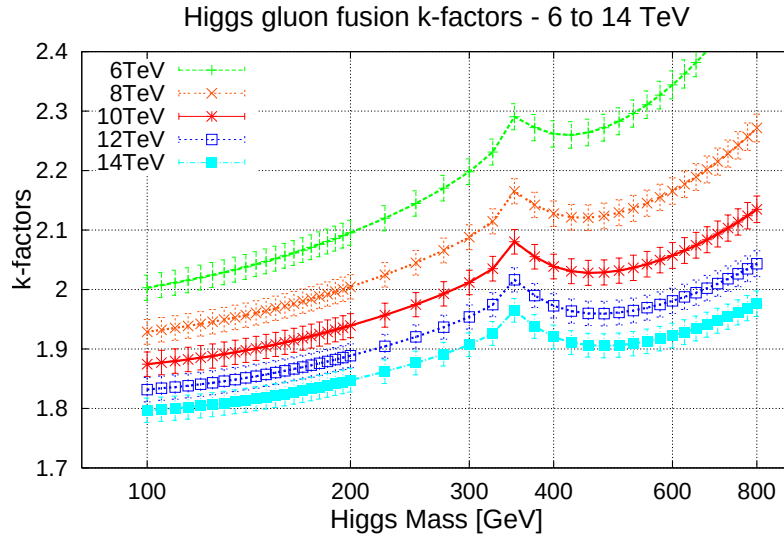


Figure 2.2: Leading Order to NLO k -factors for gluon-gluon fusion Higgs boson production mechanism for several centre-of-mass energies.

Figure 2.3 (top) shows the gluon gluon fusion NLO cross-section as function of m_H and $\sqrt{s}$.

Chapter 2. Standard Model Higgs boson production

In the gluon fusion mechanism, for a m_H of 130 GeV, one would expect to produce 43% less Higgs boson particles if the center-of-mass energy beam is decreased from 14 to 10 TeV, and 70% if it is decreased to 7 TeV. The bottom plot on Fig. 2.3 shows the $\sigma_{ggF}^H \times \text{BR}_{H \rightarrow ZZ}$. A clear suppression in the region close to the WW mass is observed.

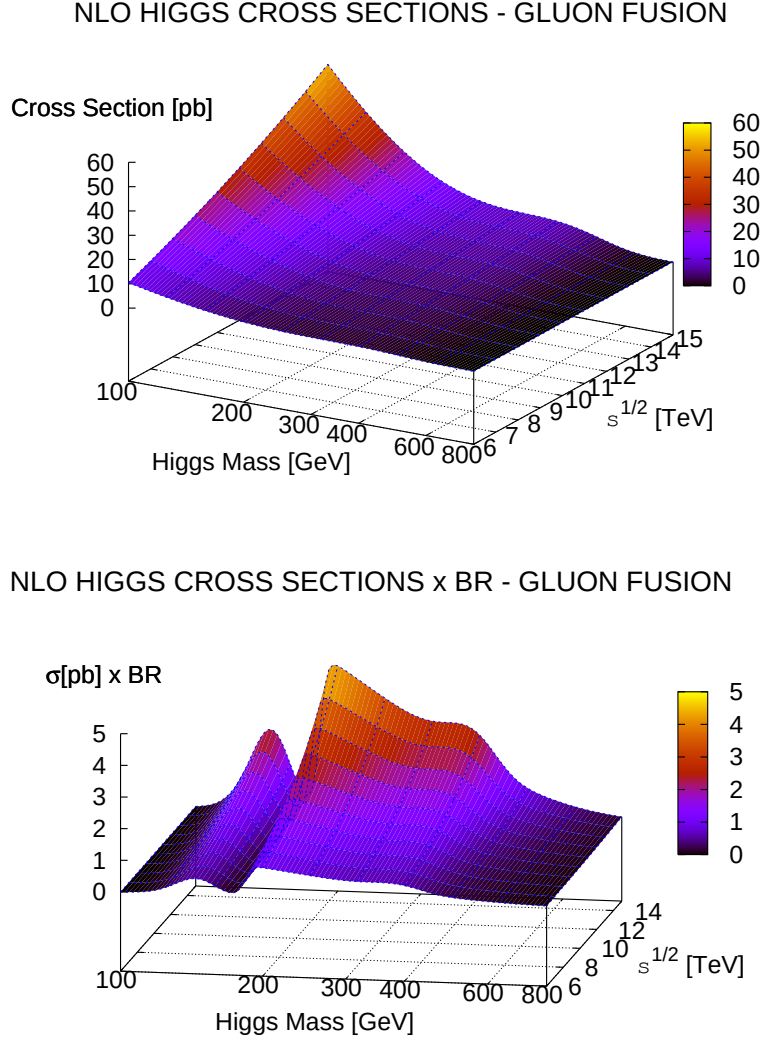


Figure 2.3: Top: Production cross-section for the SM Higgs boson in the gluon-gluon fusion mechanism as function of the Higgs boson mass and the centre-of-mass energy. Bottom: same as top plot but cross-section times ZZ Branching Ratio, both cross-sections are estimated at NLO of α_S

2.1.2 Vector boson fusion

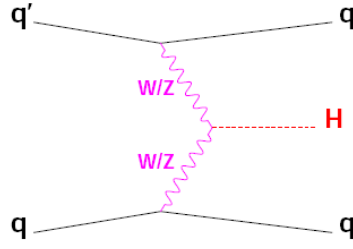


Figure 2.4: Leading order Feynman diagram for vector-boson fusion SM Higgs boson production.

The production of a SM Higgs boson in association with two hard jets in the forward (and backward) regions of the detector is an important mechanism for Higgs boson searches at the LHC. It is particularly important because it directly allows the coupling measurement of the Higgs boson with the W and Z bosons. For such a measurement it would be necessary to reject events produced through the gluon fusion channel in association with 2 jets. Although the final state is similar, the kinematics of the jets are quite different, an explicit requirement on the opening angles in the pseudorapidity plane as well as an invariant mass cut on the dijet systems are normally used, these are known as VBF cuts.

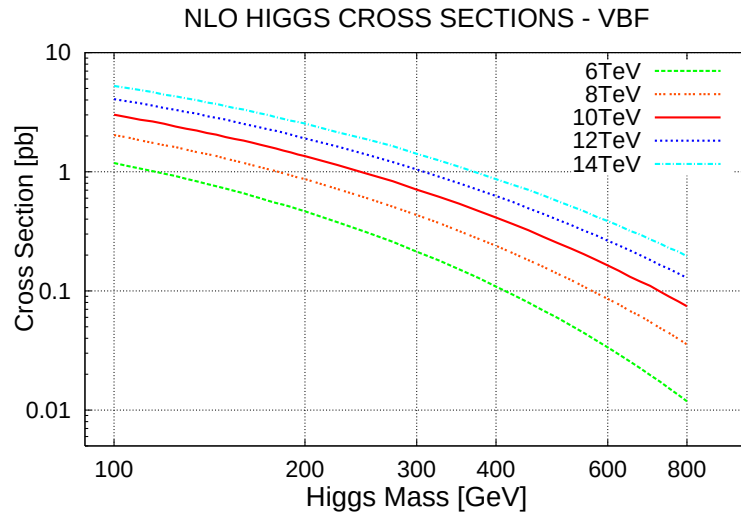


Figure 2.5: Production cross-section for the SM Higgs boson in the VBF mechanism as function of the Higgs boson mass for different centre-of-mass energy.

As s -channel diagrams and interference effects tend to be suppressed when imposing VBF cuts, the cross-section can be approximated by the contribution of squared t - and u -channel diagrams only without their interference. The program `vv2H` performs the exact NLO calculation was used to obtain a set of cross-section for several centre-of-mass energy and m_H ranges from 100 to 800 GeV, Fig 2.5 shows some of these results.

2.1.3 “Higgs-strahlung”

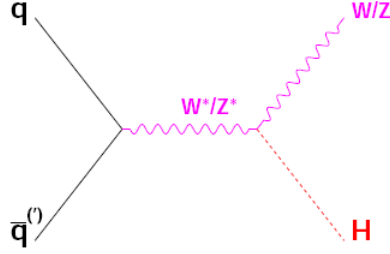


Figure 2.6: Leading order Feynman diagram for the production of the SM Higgs boson in association with a W or a Z boson.

The Higgs boson production in association with a weak vector boson (see Fig. 2.6 for Feynman diagram) is known as Higgs-strahlung [32]. This channel also have several advantages, in particular HO corrections to the LO diagrams can be obtained from the analogy with the Drell-Yan processes. This channel is important at the LHC searches because the extra presence of the W or Z , allows to exploit the large branching fraction of the Higgs boson decaying hadronically and still be able to trigger the event tagging the charged lepton(s) that would eventually come from the leptonic decay of the $W^\pm \rightarrow \ell^\pm \nu$ or the $Z \rightarrow \ell^+ \ell^-$. Unfortunately the sensitivity of this search is largely affected by the large multi-jet backgrounds which need to be controlled from data; in addition the top pair production also becomes important since the $t \rightarrow Wb$ decays could also produce a similar signature of charged leptons and two real b jets in the event.

Figure 2.7 shows the cross-sections obtained with the VH2V program. These set of numbers were estimated for $\sqrt{s}$ varying from 6 to 14 TeV and exploring the low m_H region (< 200 GeV) where these mechanisms can be better used in conjunction with the $H \rightarrow b\bar{b}$ decay mode.

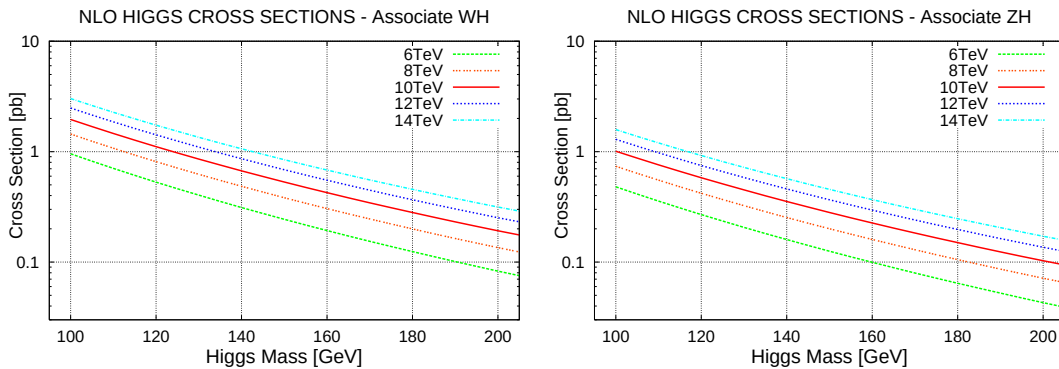


Figure 2.7: Production cross-section for the SM Higgs boson when it is produced in association with a W (Right) or Z (Left) bosons for different centre-of-mass energy hypotheses.

2.1.4 State-of-the-art Higgs boson cross-sections and branching ratios

The studies presented along the earlier sections of this chapter, done in 2009, triggered the creation of a task force aimed to coordinate a common theory recommendation for the Higgs boson analyses done at the LHC experiments. Calculations were further refined as the time passed by. The cross-sections for the gluon-fusion process were calculated to NNLO in QCD [29–31, 33–35] under the effective theory approximation, adding an extra $\sim 30\%$ on the NLO prediction. In addition, QCD soft-gluon resummations calculated in the NNLL approximation are applied for the gluon fusion process [36]. NLO EW corrections are also applied [37, 38]. These results are compiled in Refs. [39–41] assuming factorisation between QCD and EW corrections. The cross-sections for VBF processes are calculated with full NLO QCD and EW corrections [42–44], and approximate NNLO QCD corrections are now available [45]. The associated productions with a W or Z boson are calculated at NLO [46] and at NNLO [47] in QCD, and NLO EW radiative corrections [48] are applied.

The uncertainty in the production cross-section due to the choice of QCD scale is typically $^{+12}_{-8}\%$ for the gluon fusion process, and $\pm 1\%$ for the VBF process [49]. As it discussed in Chap. 1, the uncertainty in the production cross-section due to the PDF choice and α_s is an important component of the uncertainty. It was finally agreed to be $\pm 8\%$ for gluon-initiated processes and $\pm 4\%$ for quark-initiated processes [18, 50–52].

The Higgs boson decay branching ratio [53] to the four-fermion final state is predicted by PROPHECY4F [54–56], which includes the complete NLO QCD+EW corrections and leading two-loop heavy Higgs boson corrections to the four-fermion width.

The various independent calculations were found to be in very good agreement. They were compiled on a single document [49]. On this report, the agreed cross-section values for the main production mechanisms, the decay branching ratios and most important the systematic uncertainties associated with each calculation were published.

The importance of this coordinated recommendation, becomes evident once several searches are combined, not only combinations within one experiment but also combinations between LHC experiments and eventually with the Tevatron's results. Figure. 2.8 summarises the cross-section predictions once all the described corrections documented in [49] are applied.

On Fig. 2.9, the predicted decay branching ratios are displayed with their correspondent uncertainty. In the low m_H region, below twice the W boson mass, the $b\bar{b}$ decay mode is preferred. Although the $\gamma\gamma$ decay has a quite small branching fraction, the acceptance and resolution of the calorimeters in the LHC detectors were optimised to tag this signal on the top of a falling smooth background. For large m_H , (larger than ~ 200 GeV), the Higgs boson preferred to decay into a pair of weak bosons with the $H \rightarrow WW$ being roughly a factor of two larger than the ZZ decay probability. The W and Z bosons tend to mostly decay into a pair of quarks, with a bit less than 70%; the decays to leptons filled the remaining 30% distributed as: $W \rightarrow e\nu$, $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ approximately 10% each, while for $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$ each with a bit more than 3.3% and $Z \rightarrow \nu\nu$ about 20%.

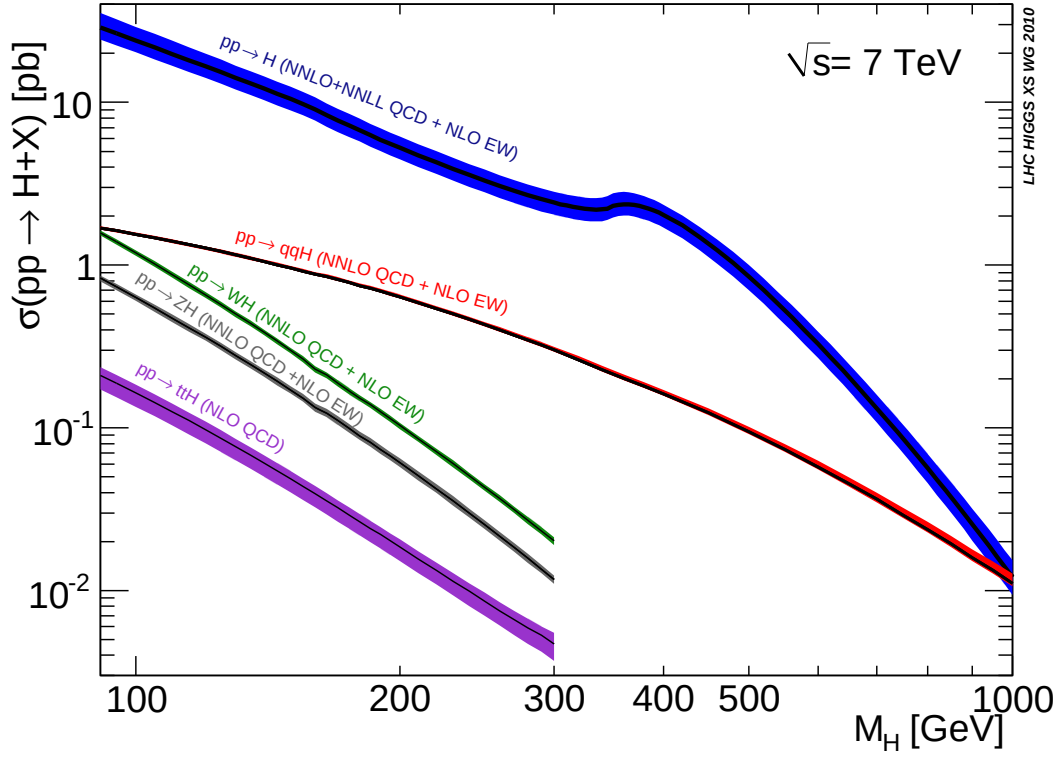


Figure 2.8: State-of-the-art inclusive Higgs boson cross-sections [49].

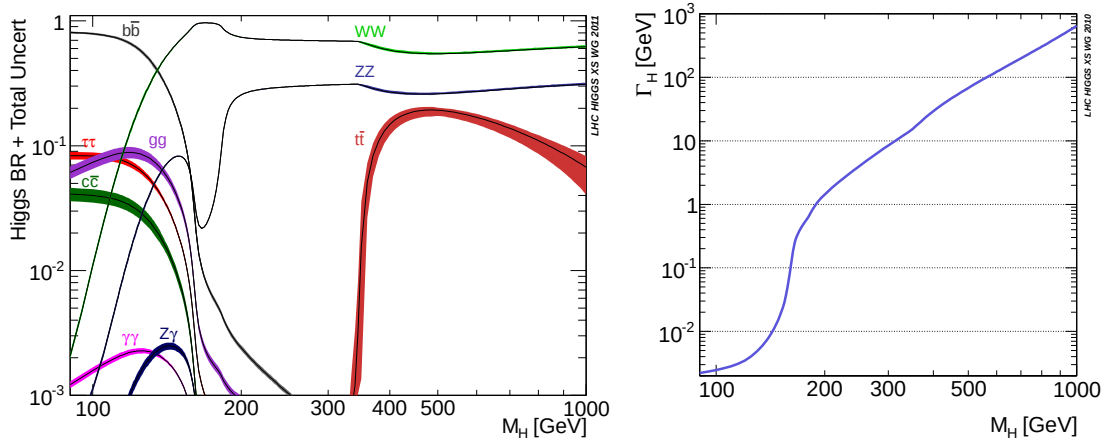


Figure 2.9: Left: Higgs boson decay branching ratios with their corresponding theory uncertainties. Right: Higgs boson width under the relativistic Breit-Wigner approximation [49].

The decay ratios of the Higgs boson is predicted to have an explicit dependency with its natural width (See Fig. 2.9 (Right)). Although the decay predictions and lineshape are well known for low m_H , it is no longer the case for large Higgs boson mass hypothesis, where the ad hoc relativistic Breit-Wigner approximation breaks apart. This particular corner of the search

phase space is further discuss in Chap. 5 Sec. 5.1.

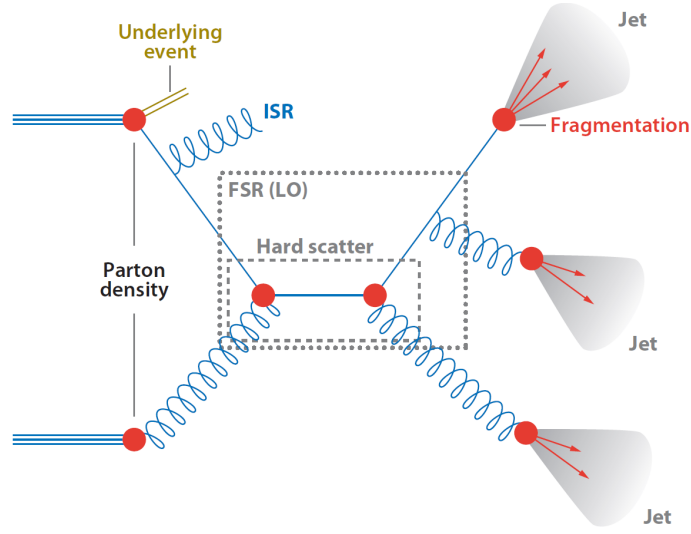


Figure 2.10: Hadron-Hadron collision diagram.

Since the LHC is a Hadron collider, one expects the presence of extra hadronic activity together with the Higgs boson $pp \rightarrow H + X$. Jets in a particular Higgs boson event could come from many different sources, initial or final state radiation (ISR, FSR), underlying event (UE) activity, pileup: secondary interactions occurring simultaneously in an event (see Fig. 2.10) or from matrix element diagrams (like the VBF signature with two forward jets or a gluon fusion diagram where the quark triangle becomes a box allowing an extra jet to be radiated in the additional vertex).

These extra jets in the event can be tagged or vetoed to further reduce possible SM backgrounds having the same or similar signature as Higgs boson. Nevertheless it is important to properly quantify the systematic uncertainty that is introduced once information about jet presence or absence is required. During 2011, a second report aimed to address this concern was published by the community [49, 57].

2.2 Experimental searches and electroweak constraints

At the moment of writing this document, direct searches performed at the CERN Large Electron-Positron Collider (LEP) have excluded at a 95% confidence level (CL), the production of a SM Higgs boson with mass less than 114.4 GeV [4].

The Fermilab Tevatron $p\bar{p}$ collider which after a successful two-phased runs of more than two decades stopped operations on September 2011 collected a total of $\int \mathcal{L} dt = 10 \text{ fb}^{-1}$ of 1.96 TeV data on each of its two experiments, the DØ and CDF detectors. Results combining a large fraction of the data analysed on both detectors were released during March 2012. In Fig. 2.11 it is shown an updated exclusion range, where the existence of the Higgs boson is ruled out at 95% CL in the region $147 < m_H < 179 \text{ GeV}$ [5, 6, 58]. This sort of direct searches could typically apply to fermiophobic Higgs boson (as mentioned on Chap. 1) on a looser extend; but dedicated analyses can profit from the enhanced branching ratios of final states like $h^0 \rightarrow \gamma\gamma$ (though a W loop instead of a quark loop), the $h^0 \rightarrow WW$ or $h^0 \rightarrow ZZ$, as well as the larger production cross-sections for VBF and associated production mechanisms. The latest results from the Tevatron excludes a fermiophobic Higgs boson below 115 GeV [59].

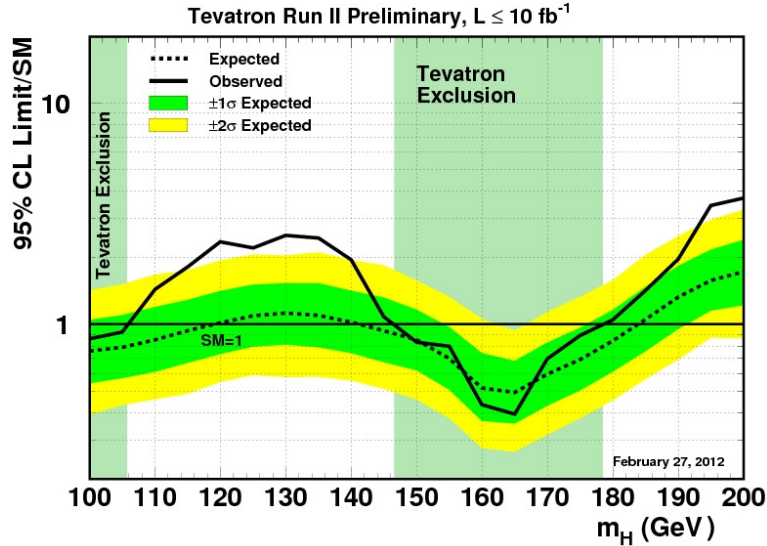


Figure 2.11: Combined SM Higgs boson exclusion limits at 95% CL using up to 10 fb^{-1} of $p\bar{p}$ data (Run II) on each of Tevatron's detectors [58].

Precise electroweak measurements could also help to set indirect constraints on the expected mass of the Higgs boson particle assuming that the dominant virtual contributions to the electroweak observables arise through vacuum polarisation loops. A global multidimensional fit can be performed on a set of parametrised oblique corrections [60]. A p -value can be extracted and compared against different m_H assumptions. A release of a new set of results on March 2012, included the world average W mass measurement [61] ($m_W = 80.385 \pm 0.015 \text{ GeV}$) and width $\Sigma_W = 2.098 \pm 0.048 \text{ GeV}$; as well as the most recent Tevatron's top quark mass measurement ($m_{top} = 173.3 \pm 0.9 \pm 0.6 \text{ GeV}$) [62] as shown in Fig. 2.12 (Right). If constraints

2.2. Experimental searches and electroweak constraints

from direct searches are included, the preferred Higgs boson mass from the global electroweak fit is $m_H = 94^{+29}_{-24}$ GeV, with an upper-bound at $m_H < 152$ GeV at 95% CL. Figure 2.12 (Left) shows the different results obtained since 2009. The indirect fit constraint the Higgs boson to be light.

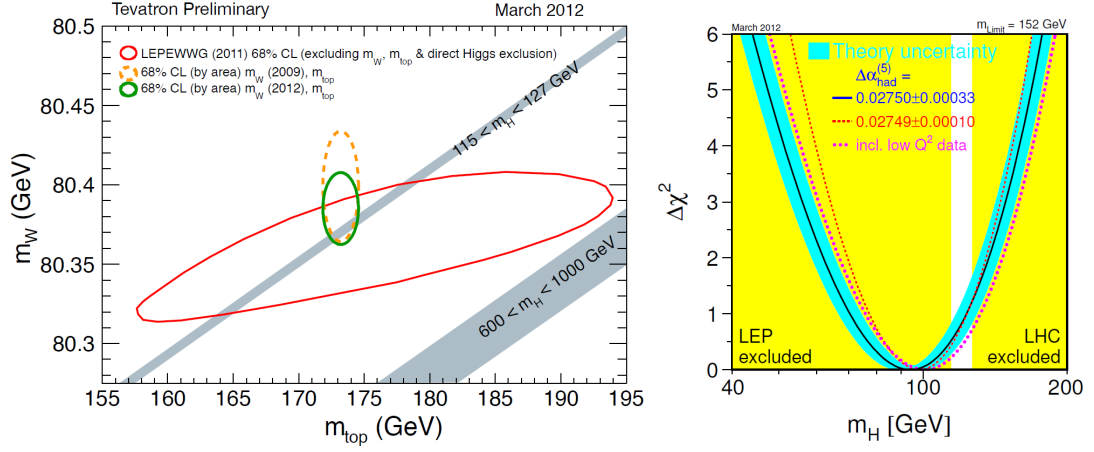


Figure 2.12: Indirect estimation of preferred Higgs boson mass valued using electroweak fitted data. It includes the most recent measurements of the top quark and W boson masses [58] (Right).

3 The Large Hadron Collider and the ATLAS experiments



"I didn't know CERN was on the web"

Anonymous comment to an online article reporting the LHC start-up.

This chapter describes the Large Hadron Collider experiment and its detectors. The different technologies that are used by each of the subsystems in the ATLAS detector aimed to measure specific properties of the particles passing through are also introduced. The second part of the chapter gives some further details of the computing and data models used by the ATLAS collaboration. Some studies used to quantify and evaluate the feasibility of a software and hardware infrastructure to be used at the last piece of the analysis chain are also presented.

The European organisation for nuclear research CERN is the biggest physics laboratory in the world, with nearly six decades dedicated to lead fundamental research disentangling the secrets of nature. Among the different projects it currently hosts, the best known is the LHC, it is said to be the biggest machine on the planet, and to be one of the most complex experiments ever dreamt and conceived.

3.1 The Large Hadron Collider

The LHC [63, 64] is the most powerful particle accelerator ever built. It was assembled in a circular tunnel of 27 km perimeter buried ~ 100 m underground replacing the glorious LEP collider. The proton and lead nuclei beams of the LHC are injected following a series of pre-boosting and pre-accelerators stages which also provide high energy particle beams to other experiments, see Fig. 3.1. Protons are extracted from Hydrogen atoms in a plasma. They are then accelerated through Radio Frequency (RF) Quadrupoles reaching 750 keV. From there, the

Chapter 3. The Large Hadron Collider and the ATLAS experiments

Linac-2 facility accelerates the proton beams to 50 MeV; then the Proton Synchrotron Booster, and the Proton Synchrotron (PS) increase the beam energy to 1.4 and 25 GeV respectively. The Super-Proton Synchrotron (SPS) is the last step of the injection chain where proton bunches at a centre-of-mass energy of 450 GeV are delivered. The beams at the LHC are accelerated along two adjacent beam pipes, collisions occur in four different places, interaction points (IP), where particle detectors were built.

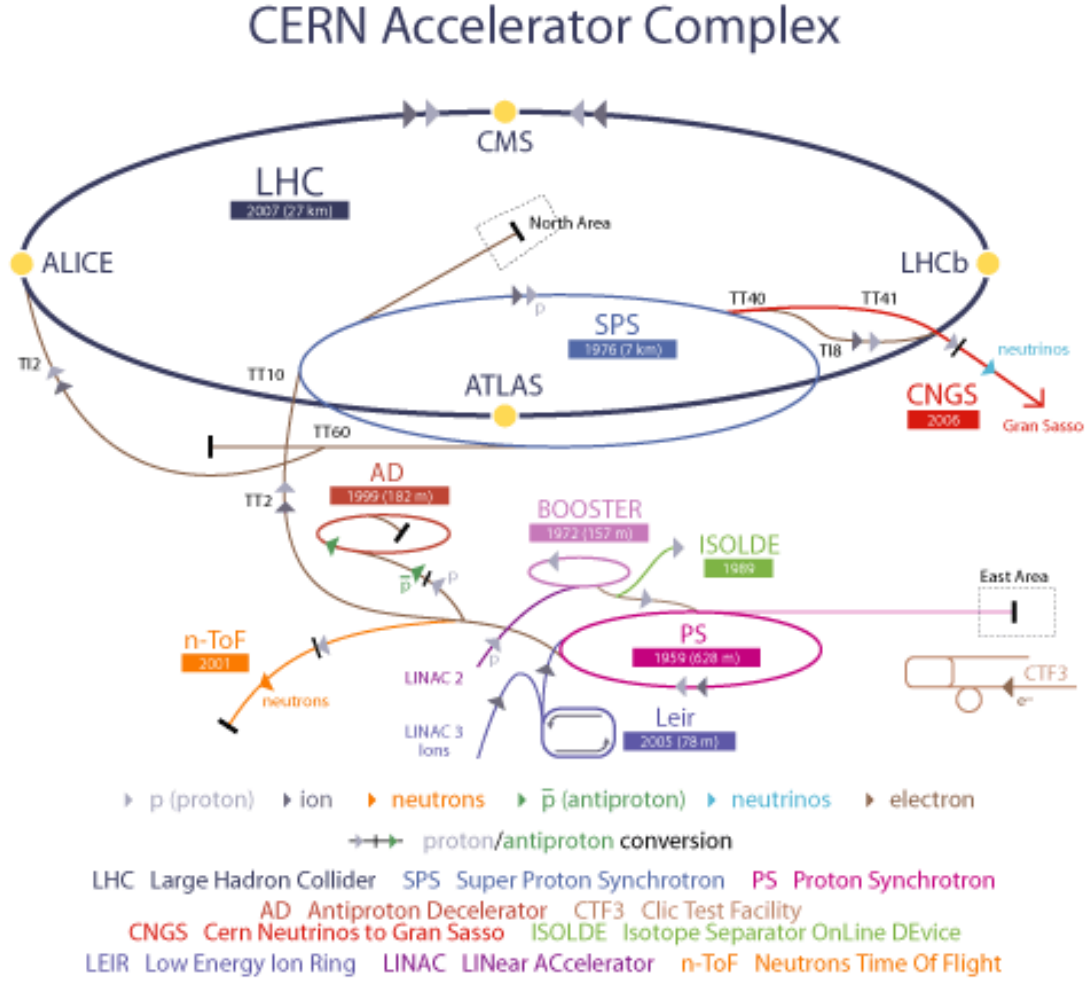


Figure 3.1: CERN accelerator complex [65].

The LHC was designed to operate at a centre-of-mass energy of 14 TeV and instantaneous luminosities reaching $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Instantaneous luminosities are calculated based on beam parameters such as the number of bunches per beam (n_b up to 2808), the number of protons per bunch ($N_b \sim 1.15 \times 10^{11}$), the revolution frequency ($\nu \sim 11.2 \text{ Hz}$, one bunch crossing every 25 ns) and the geometrical factor of the beams ($\mathcal{F}$ which is proportional to the

betatron function β^*):

$$\mathcal{L} = \frac{N_b^2 n_b v}{\mathcal{F}} \quad (3.1)$$

The six main experiments of the LHC are:

- **ATLAS**

ATLAS [66] is a multi-purpose detector, it is described in detail in the following section.

- **CMS**

The **Compact Muon Solenoid** [67] is also a general purpose detector optimised to measure high energy particles covering most of the solid angle. The huge solenoid superconducting magnet producing a magnetic field of almost 4 T, its colossal crystal calorimeter and a series of densely arranged muon chambers allow unprecedented momentum and energy measurements keeping high detection efficiencies. It shares a similar physics program with the ATLAS detectors, where large amount of luminosity are desirable.

- **ALICE**

It is a **Large Ion Collider Experiment** [68] designed to explore the primordial state of matter before hadrons were formed. The high energy densities needed to form the so-called quark-gluon plasma are achieved by colliding lead ions at centre-of-mass energies up to 1.15 PeV. The ALICE subsystems are designed to cope with the large amount of information produced in nuclei collisions.

- **LHCb**

The **LHC “beauty”** experiment [69] was built to probe CP -violating processes and rare decays in B mesons. It aims to explain why the universe does not appear to have equal amounts of matter and anti-matter. The LHCb experiment is an asymmetric detector which surrounds the collision point along the very forward pseudorapidity region approaching as close as possible the IP. Opposed to CMS and ATLAS, the LHCb physics’ program requires clean events (low pile-up) while large amounts of luminosity are not necessarily needed.

- **Totem and LHCf**

The **TOTAL Elastic and diffractive cross-section Measurement** experiment [70] and the **LHC forward** experiments [71] explore the phenomena that can be studied by detecting the particles that are scattered very close to the beam pipes. This includes total $p - p$ cross-sections, proton structure measurements, and the usage of these forward particles to recreate the showers produced by cosmic rays in the atmosphere.

3.2 The ATLAS detector

The ATLAS detector has a forward-backward symmetric cylindrical geometry with 25 m diameter and 44 m long; it is the biggest of the LHC experiments. Its major components are the inner detector (ID) the electromagnetic and hadronic calorimeters, and the muon spectrometers.

ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the centre of the detector and the z -axis coinciding with the axis of the beam pipe. The x -axis points from the IP to the centre 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 beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

The ATLAS subsystems gather hermicity (full azimuthal angle coverage and large pseudorapidity acceptance: $|\eta| < 2.5$ for its ID and $|\eta| < 4.8$ for its calorimeters), a high precision track momentum and excellent electromagnetic and hadronic calorimetry capabilities.

In contrast to CMS, ATLAS uses an “air-cored” toroidal barrel and end-cap superconducting magnets that provide a bending power of up to 6 Tm in the pseudorapidity range of 0 - 1.3; it also uses an transverse accordion-shaped Liquid Argon electromagnetic calorimeter allowing particle vertex pointing and the usage of explicit shower-like discriminators.

ATLAS has a three-level Trigger system which is in charge of filtering events leaving only physics motivated signatures. The Trigger and the data acquisition systems are in charge of selecting and shipping the relevant data to the main computing facility, where they are reprocessed and sent to storage for posterior performance or physics studies. On this section the different sub-detectors, the Trigger, the data acquisition and computing infrastructure of the ATLAS experiment are introduced.

3.2.1 Inner Detector

The ID is immersed in a magnetic field of 2 T produced by the central solenoid. It consists of three subsystems based on two main technologies. The Pixel detector is the closest to the IP, followed by a second Silicon-like array made of micro-Strips, and the Transition radiation tracker which uses fast response straw detectors. It allows precise measurements of the trajectories left by charged particles. This is a crucial piece of information to accurately reconstruct charged leptons as well discriminate jets produced by heavy quarks which typically have longer life times.

Pixel detector - PIX

The Pixel detector has the largest number of channels of all of the ATLAS subsystems (about 80.4 M with the smallest sensor covering an area of $50 \times 400 \mu\text{m}^2$). Its high granularity provides high precision measurements very close to the beam pipe (see Fig. 3.3 Right). As it is shown in

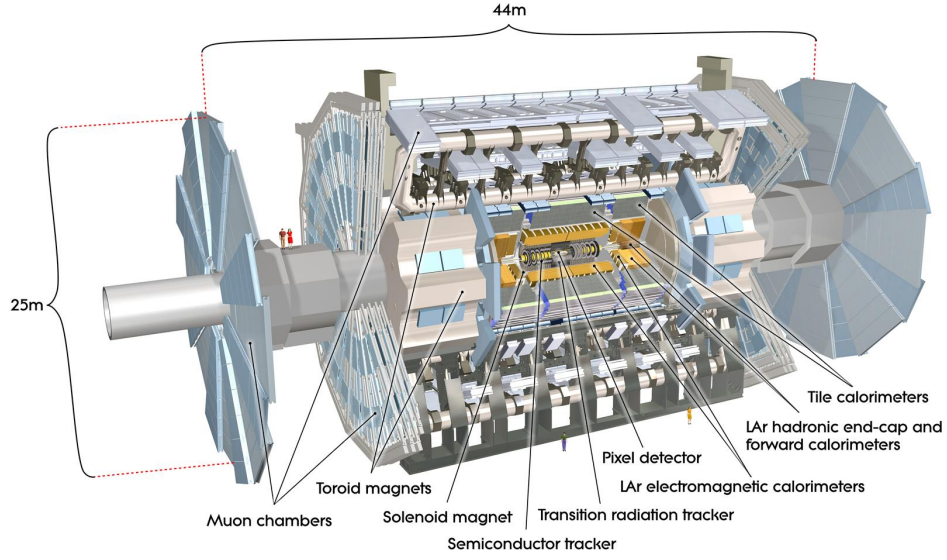


Figure 3.2: Components of the ATLAS detector [72].

Figs. 3.3 and 3.4 it consists of three modules in the barrel and a set of disks perpendicular to the beam pipe on each side; reaching a pseudorapidity acceptance of $|\eta| < 2.5$. It is designed to stand more than 300 kGy of ionising radiation and over 5×10^{14} neutrons per cm^2 over ten years of operation. Currently the construction of an additional insertable module (B-Layer) [73] even closer to the beam pipe is ongoing. It is expected to be installed during the detector upgrade for the sLHC [74].

Silicon micro-Strip Tracker - SCT

The SCT provides up to eight precision measurements per track using four stereo strips where the layers on each pair have an offset of 40 mrad. The intrinsic accuracy on each module is approximately $17 \mu\text{m}$ ($R - \phi$) and $580 \mu\text{m}$ (z) in both the barrel and the endcaps. The SCT has an inner radius of 250 mm, an outer radii of about 550 mm and some 5.4 m length.

Transition Radiation Tracker - TRT

The TRT uses a large number of 4 mm diameter straw-like detectors designed to operate at very high rates present at the LHC. Each high P_T track passing through leaves between 30 to 36 hits, reaching a $R - \phi$ precision of about $130 \mu\text{m}$. Electron identification is enhanced by transition radiation with the usage of interleaved polypropylene (fibres in the central region and foil in the endcaps). The TRT length of 5.4 m only cover a pseudorapidity region within $|\eta| < 2.0$

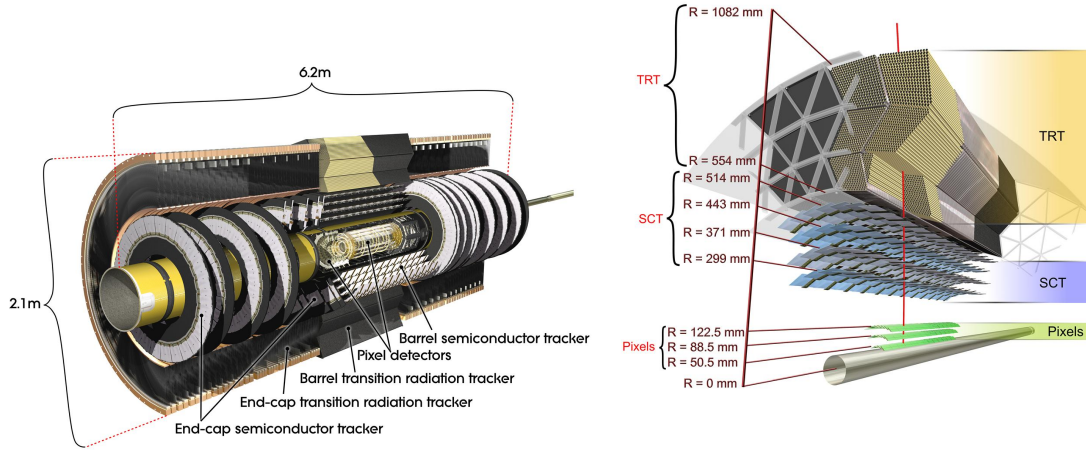


Figure 3.3: Subsystems of the ATLAS inner detector [72].

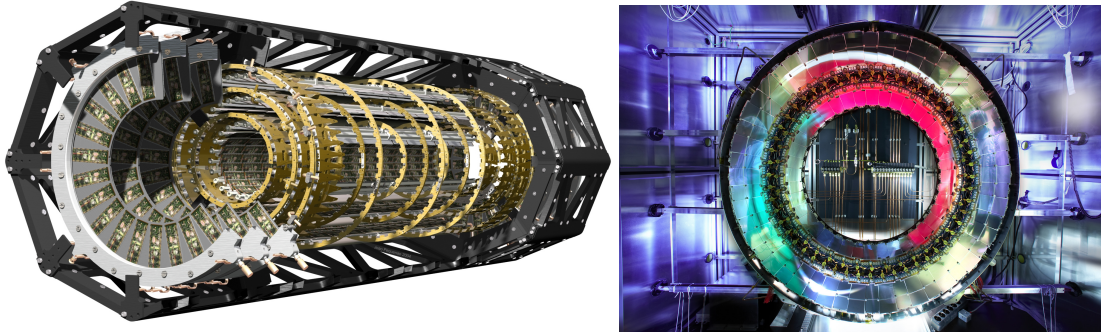


Figure 3.4: Left: Layout of the Pixel detector. Right: Photograph of the Silicon micro-Strip Tracker barrel under construction [72].

3.2.2 Calorimeters

The ATLAS electromagnetic and hadronic calorimeters use two different technologies. Figure 3.5 (Left) has a schematic view of the barrel, endcap and forward components

Electromagnetic Liquid Argon calorimeter - LAr

The electromagnetic (EM) calorimeter has a large pseudorapidity acceptance $|\eta| < 3.2$ it is a Lead Liquid Argon detector with accordion-shaped Kapton electrodes and lead absorber plates with no azimuthal cracks. The barrel reach $|\eta| < 1.475$ and the endcaps $1.375 < |\eta| < 3.2$. It has a thickness of >22 radiation lengths (X_0) in the barrel and $X_0 > 22$ in the endcaps. As it can be seen in Fig. 3.5 Right, the central region of the EM is made of three layers plus a pre-sampler with fine granularity ($\eta \times \phi = 0.025 \times 0.1$). The first sampling is sub-segmented in η ($\eta \times \phi = 0.025/8 \times 0.1$), while the second sampling is sub-segmented in ϕ ($\eta \times \phi = 0.025 \times 0.025$). Finally the third sampling is segmented into cells of $\eta \times \phi = 0.025 \times 0.05$.

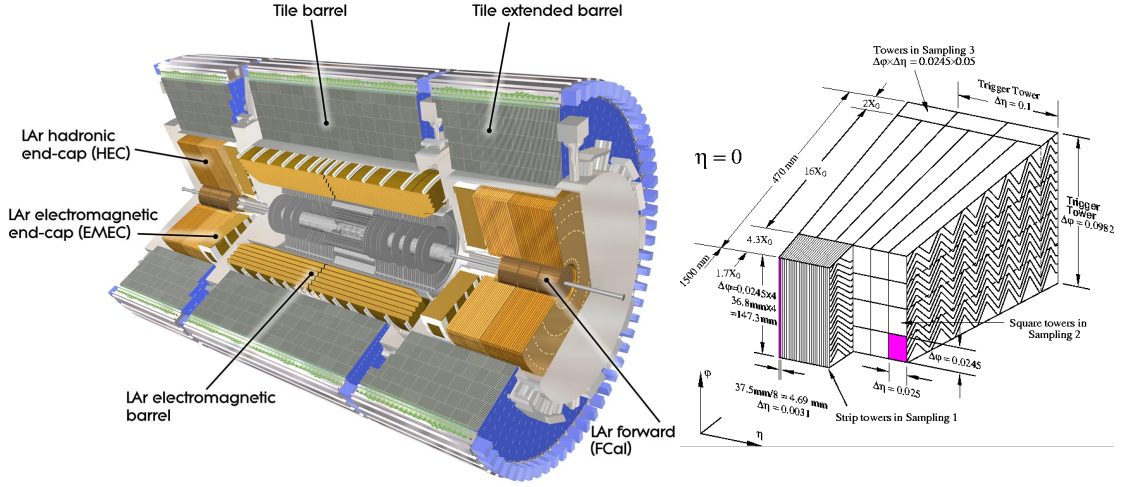


Figure 3.5: Layout of ATLAS electromagnetic and hadronic calorimeters [72].

The fine granularity implies that a typical photon or electron would cluster in several tens of cells. This allows the usage of the shape information of shower deposition to discriminate electrons and photons from jets.

Hadronic calorimeters

The barrel of the the hadronic calorimeter uses iron absorbers and plastic scintillating tiles as active material. It is divided into two regions, $|\eta| < 1.0$ and $0.7 < |\eta| < 1.7$ (extended barrel). It is also segmented longitudinally into three layers. The effective granularity varies between $\eta \times \phi = 0.1 \times 0.1$ and 0.2×0.1 . The fast signals produced by each scintillating tile are read out by wavelength shifting fibres into two separate photomultipliers.

The endcap and forward regions of the hadronic calorimeters use LAr as active material and cooper (and tungsten) as absorber. The endcap hadronic calorimeter consist of two independent wheels built out of 32 modules. The forward calorimeter covers the pseudorapidity region between 3.1 and 4.9, and it is split in an electromagnetic and a hadronic components. The ATLAS calorimeters provide an excellent jet energy resolution this is crucial for a correct measurement of missing transverse energy (E_T^{miss}).

3.2.3 Muon spectrometer - MS

The muon spectrometer consists of four different subsystems based on different technologies capable to perform high precision tracking and also to respond to the required fast triggering times. It is immersed on a toroidal magnetic field produced by an array of air-cored superconducting magnets (a barrel toroid and two endcap magnets) providing a powerful bending power and minimising the degradation of resolution due to multiple scattering. Figure 3.6

shows the layout of ATLAS magnetic systems and its muon detectors.

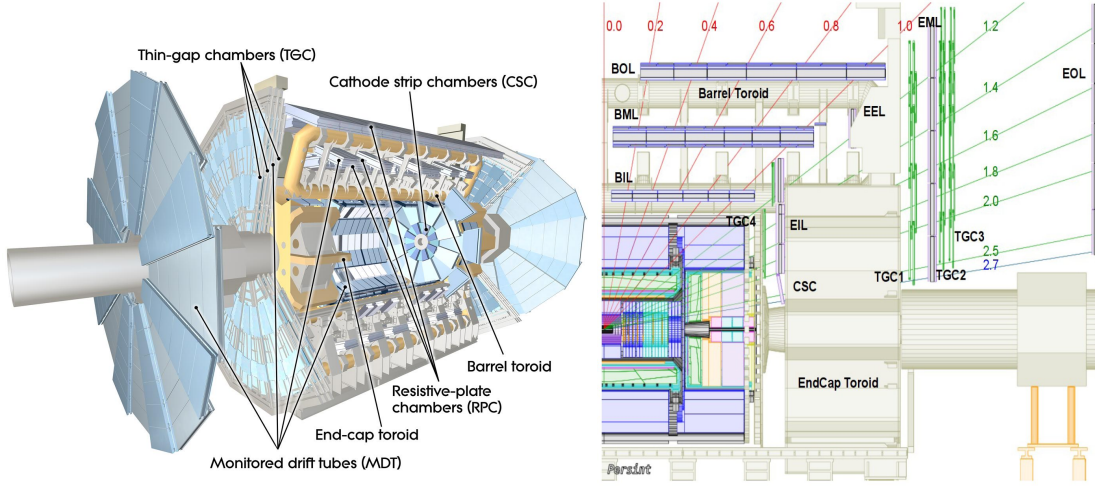


Figure 3.6: Left: Layout of the ATLAS muon spectrometers. Right: Pseudorapidity reach of the different ATLAS muon subsystems [72].

Muon tracks are measured by three concentric cylindrical stations in the barrel and 3×2 endcap (A and C) wheels located at $|z|$ 7.4, 14, and 21.5 m. In both the barrel and the endcaps a 16-fold segmentation in the azimuthal plane was chosen following the 8-fold array of the toroidal magnetic systems.

Monitored Drift Tubes chambers - MDT

The MDTs are based on an array of 30 mm diameter aluminium tubes each with a central tungsten-rhenium alloy wire and filled with a gas mixture mostly made of argon. Each tube is kept at high potential differences (3 kV), the drifting time in any given point does not exceed the 700 ns. There are about 1200 chambers covering a region up to $|\eta| < 2.7$. The system is arranged into multilayer chambers with enough hit redundancy to reach $35 \mu\text{m}$ track precision.

Cathode Strip Chambers - CSC

The CSCs have a higher granularity than the MDTs, this is needed to cope with the more demanding background present in the forward regions. The pseudorapidity region covered by the CSC is $2.0 < |\eta| < 2.7$. The CSCs are multi-wired proportional chambers made of halfway suspended anode wires between two parallel plates covered with cathode strips, one oriented parallel and the other perpendicular to the wires; each module is made of four wire planes. The short electron drift times (~ 40 ns), the good time resolution (~ 7 ns) and the low neutron sensitivity allow muon track reconstructions of $45\text{--}60 \mu\text{m}$ in the bending direction and 0.5 cm in the transverse plane.

Resistive Plate Chambers - RPC

The RPCs are gaseous detectors, made of two parallel highly electrical resistant plastic plates separated by insulating spacers (2 mm) and filled with a mixture of $C_2H_2F_4$, Iso- C_4H_{10} and SF_6 . The RPCs cover the central region ($|\eta| < 1.05$) and since the readout does not rely on electrodes drift-charge collection can provide a time space-time resolution of $1\text{ cm} \times 1\text{ ns}$ ideal for trigger.

Thin Gap Chambers - TGC

The TGCs cover a region between $1.05 < |\eta| < 2.4$. Their design is similar to the CSCs with the difference that the anode wires distances are slightly larger (1.8 mm instead of 1.4 mm) and that in the bending direction the position measurement is given by the anode wires instead of the strips. The azimuthal granularity of the TGCs is 2-3 mrad and the redundancy allows up to 20 wire measurements for a precision smaller than 7.2 mm.

3.2.4 Studies of muon ID and MS alignment with the first Z boson candidates

The alignment of the muon spectrometer is a key issue for accurate reconstruction of muon tracks. The large global dimensions of the spectrometer forbids the positioning of the chambers at the micrometre level. Chamber deformations and positions are constantly monitored using different sorts of data, in particular: cosmic rays, data taken without magnetic fields or filtered data containing well known resonances like the $Z \rightarrow \mu\mu$ process. Most of the corrections (< 1 cm are normally performed at the software reconstruction level).

ATLAS has two independent muon reconstruction algorithms that use the full set of track information in the inner and outer parts of the detector. The MuID reconstruction algorithm fits simultaneously the hits in the ID and the MS, while the STACO algorithm performs a fit of independently reconstructed two sub-segments. Further details of muon reconstruction and identification can be found in Ref. [75]. The performance of the MS can reach resolutions from 2-5% for muons with transverse momenta (p_T) in the tens of GeV.

Studies aimed to check the ID-MS relative alignment using the first few thousand $Z \rightarrow \mu\mu$ events collected by the ATLAS detector were performed during the summer of 2010. The event candidates were selected by requiring:

- **ATLAS Good Run list requirement:** All subsystems passing online data quality checks.
- **Muon requirements:**
 - STACO and MuID reconstruction algorithms were used:
 - $p_T^\mu > 15$ GeV and $|\eta| < 2.4$
 - $p_T^{MS} > 10$ GeV, and $|p_T^{ID} - p_T^{MS}| < 15$ GeV
 - Close to at least one good reconstructed vertex within z : $|z_0 - z_{vtx}| < 10$ mm
 - Isolation: Relative track isolation $\frac{\sum_{\text{cone40}} p_T^{ID}}{p_T} < 0.2$
- **At least two high p_T muons:** $p_T > 20$ GeV, with opposite charge.
- **Invariant mass window:** $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$

The sample used corresponded to an integrated luminosity of about $\int \mathcal{L} dt = 8.7 \text{ pb}^{-1}$. The amount of collected events allowed a coarse binning on different kinematic variables to study detector resolution in the regions of few tens of GeV. These regions were:

- Barrel/endcap configurations.
- Pseudorapidity (cumulative) $\rightarrow |\eta| : 0.4 - 2.4$
- Tagging a μ in the barrel and looking at the position in ϕ for the second μ separating in encap (A or C) and charge. (4 quadrants in ϕ)

To allow the extraction of the detector resolution, a fit was performed using a model containing: a ad-hoc relativistic Breit-Wigner to described the Z resonance; convoluted with a Gaussian function to extract the resolution component plus an exponential function to account for the Low Drell-Yan contribution and other background contaminations.

$$f(x) = \frac{1}{(x - m_Z)^2 + \frac{1}{4}\Gamma^2} \otimes \exp\left(-\frac{(x - m_Z)^2}{2\sigma^2}\right) + e^{a \cdot x} \quad (3.2)$$

The natural width of the Z boson, Γ , was allowed to float on a limited range in order to avoid over-constraints on the resolution width. It is known that this model does not fully describe the tails of a Z boson peak. A full lineshape PDF would be more appropriated, but for the scope of this first studies performed with early data, the model is sufficient given the limited statistics.

A MC simulation of $Z \rightarrow \mu\mu$ events is also fit for calibration and comparison purposes. It is worth mentioning that data is adjusted using unbinned fits (binsize could bias parameter values), while MC is fitted from binned histograms with small bin sizes and very large ($\sim 1\text{M}$ events) statistics.

Figure 3.7 shows the data fit, a resolution of $\sim 2.5\%$ on the Z reconstructed width was observed for both muon reconstruction algorithms. The full MC simulation suggests a resolution effect below 2.0% .

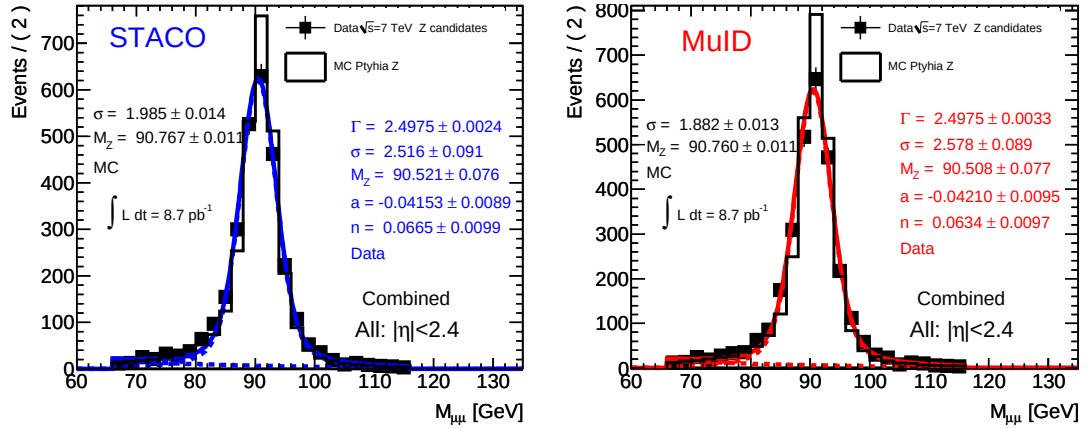


Figure 3.7: Preliminary resolution studies with $Z \rightarrow \mu\mu$ events. STACO (MuID) muon reconstruction algorithms are used on the Left (Right).

Measurement on the different pseudorapidity configurations for the muon pair (both muons in the barrel, one in the endcap and the second in the barrel, or both of the muons in the endcaps) provide specific information about the alignment and performance knowledge of each of the regions. The poorest resolution (~ 6 GeV) is observed when both of the muons are measured in the endcaps with no constraints from ID measurements.

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Central muons are normally measured with smaller uncertainties than forward ones. In Fig. 3.8 it is shown the fitted Z width resolution as function of η . Fitted values on the MC sample are also shown. These studies provided a good idea of the level of understanding of the muon system alignment for muons coming from Z decays at the time the data was collected.

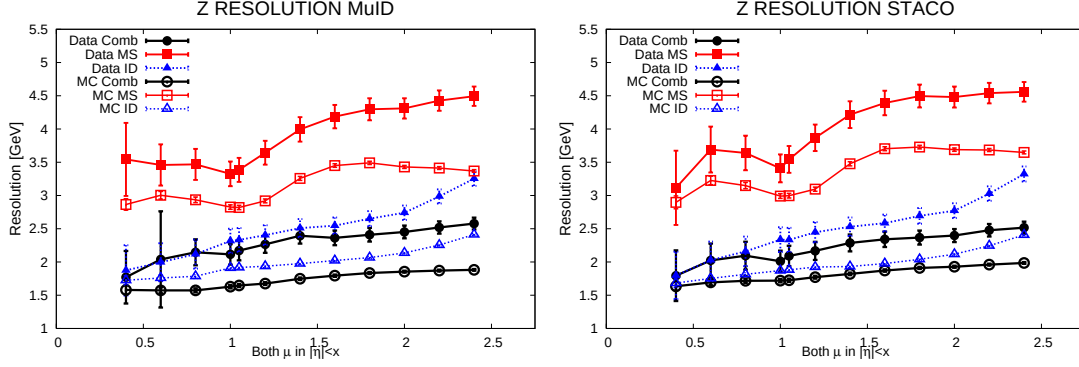


Figure 3.8: m_Z detector resolution as function of η (cumulative), for the STACO (Left) and MuID (Right) muon reconstruction algorithms.

Table 3.1, summarises the fitted expectations and observed resolution values for the different momentum measurements in the ID, the MS and with both for each of the ATLAS muon reconstruction algorithms.

Table 3.1: Resolution studies on $Z \rightarrow \mu\mu$ events

		STACO		MuID	
		DATA	MC	DATA	MC
ALL	Combined P_T^μ	2.52 ± 0.09	1.99 ± 0.01	2.58 ± 0.09	1.88 ± 0.01
	Muon Spect. P_T^μ	4.56 ± 0.15	3.65 ± 0.02	4.49 ± 0.15	3.37 ± 0.02
	Inner Track P_T^μ	3.32 ± 0.11	2.41 ± 0.01	3.25 ± 0.11	2.41 ± 0.01

Further details of these alignment checks, including best fitted peak mass and resolutions binned on samples of ϕ , muon charge, and tag-probe endcap side are given in appendix A.1.

3.2.5 Trigger and data acquisition

The trigger and data acquisition (TDAQ) infrastructure is formed by a three level online event selection. Its main purpose is to reduce the approximately 40 MHz of interaction rates (at $10^{34} \text{ cm}^2\text{s}^{-1}$) to $\sim 200 \text{ Hz}$ (that is what can be written into disk). Figure 3.9 shows the data flow through the ATLAS TDAQ infrastructure. The first level (LVL1 Trigger) is a hardware filter which using pipeline memories with signals from calorimeters and muon systems (RPC and TGC) reduces an input rate of 40 MHz ($\sim 10^9$ interactions) to about 75 kHz. The following two levels (LVL2 and LVL3) are performed at software level and are also called the High Level Trigger (HLT).

The different challenges of the LVL1 trigger are to keep the shortest latency times possible, and to identify the bunch crossing of interest; in some cases the time of flight of muons could be comparable to the bunch crossing interval (25-50 ns), and for the calorimeters a pulse could extend along several bunch crossings (150 ns). In the LVL2 trigger, a close look at the region of interest given by the LVL1 (total energy sums and η , ϕ , and p_T of the candidate/s) allows further discrimination reducing the 75 kHz input to 3 kHz. Finally a farm with more than 7000 cores allow the final event filtering (EF). In the LVL3/EF the whole events are analysed with ultra fast algorithms; information like alignment constants and magnetic field maps are used to perform partial reconstructions that allow a more specific selection of objects using the full set of ATLAS' sub-detectors. The final output rate of the HLT is of about 200 events per second, where each raw data event has some 1.5Mb of information.

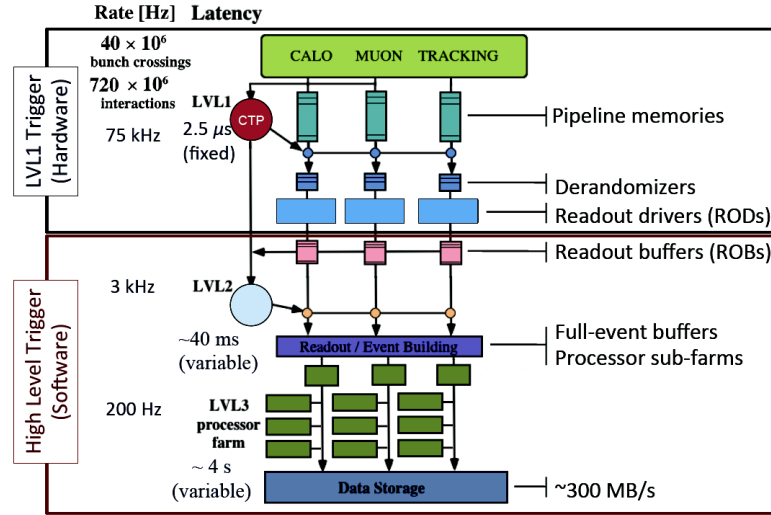


Figure 3.9: Data flow along the three level trigger and data acquisition infrastructure in the ATLAS detector [76].

The Higgs boson searches presented in this document tag the leptonic decays of the weak bosons. The goal from the trigger perspective is to keep “low” p_T muon and electron rates un-prescaled (typically in the order of 20 GeV for single lepton triggers and 12 GeV in the case

of di-lepton triggers). This is particularly important for the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ channel where leptons from off-shell W decays are expected to have relatively low p_T (most important if m_H is small $\rightarrow \sim 130$ GeV). Because of the very low rates in the $H \rightarrow ZZ \rightarrow 4\ell$ channel, the acceptance is important; fortunately the presence of four charged leptons in each event largely increase the trigger probability. In the case of $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, the fact of having each charged lepton pair coming from an on-shell and often transversely boosted Z boson guarantees that the kinematics of leptons are high enough to be robust against trigger inefficiencies.

3.3 Computing Model

With 1.5 Mb per raw-data event, rates of 200 events per second, and LHC running efficiencies surpassing the expectations, the computing power needed to fully reconstruct and analysed the LHC data is larger than any other previous physics experiment. In order to reconstruct the raw data, create Monte Carlo (MC) simulations, and most important to allow users to perform analyses at every stage of the chain, a Grid computing model based on Tiers was conceived to cope with the vast amount of information (See Fig. 3.10).

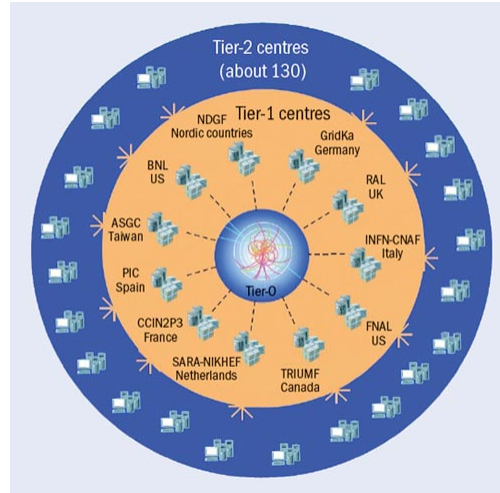


Figure 3.10: Tier-like infrastructure model used by the LHC experiments to simulate and analyse the data [76].

The Tier-0, is a large computing farm located at CERN where the prime reconstruction of events is performed. Once the data is converted into an accessible format replicas are made on eleven different Tier-1s around the planet. Several laboratories and institutions part of the ATLAS Collaboration allocate computing resources creating the so-called Tier-2s. These infrastructures are used to perform CPU and I/O intensive MC simulations and data analyses. Users from different institutions use these shared resources to perform all kind of analyses; many institutions also arrange smaller farms (Tier-3) that allow to speed up and optimise data analyses.

3.4 Studies of Tier2/3 computing performance

From the analysers side, the LHC Grid resources are heavily used to pre-filter the bulk of the desired data and MC simulations. Although these preselections can be as tight as one wants it to be, the typical outputs of the preselections could still contain several tens of Terabytes. The goal of is to find the best compromise between an output containing the information needed ¹ an a portable output size. The filtered data is normally analysed locally on clusters disposed in Tier-2 and Tier-3s.

At the University of Wisconsin in Madison, a medium-size Tier-3 is used to analyse the ATLAS data and MC simulations. Figure 3.11 shows the data flow and network organisation of the site. The desired data and MC simulation files are obtained from the Brookhaven National Laboratory (BNL) Tier-1 controlled by a dedicated server. Files are placed in a storage sub-farm, configured with the XROOTD [77] network file system. Analysers access the data using a separate link configured to serve as master of the farm running the PROOF (Parallel ROOT Facility) [78] tool. It allows the usage of resources, parallely distributing sub-jobs on each core (worker) of the cluster, prioritising the acces of the data formatted in ROOT n-tuples .

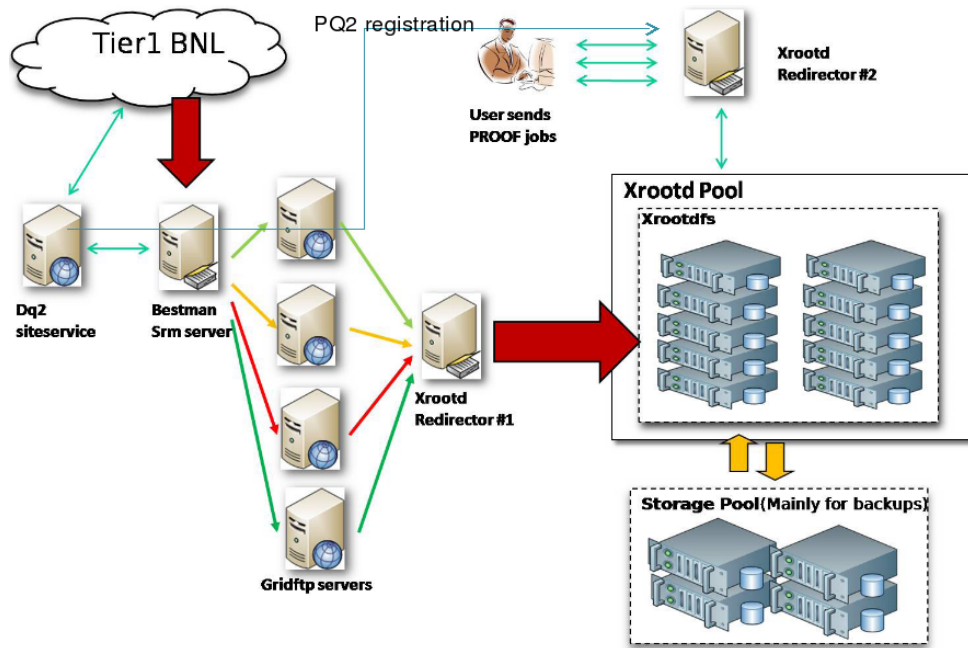


Figure 3.11: Design of the system, where data from a Tier 1 is shipped and organised on the storage farm, which later allow us to plug with the different distributed analysis tools like CONDOR BATCH or PROOF

Since the system was proved to be very efficient and robust, managers of other Tier-3 were

¹The filtered information where the subsequent analyses are done, typically requires to be accessed many times. This is the reason why filtering is crucial. Nevertheless one has to ensure that the information kept is sufficient to performed the desired studies.

interested in adopting such a structure. In 2008, an effort was created by the US-ATLAS colleagues to facilitate and quantify the needs and limitations of these clusters. The required information, included the optimal and maximum number of users and assigned cores to each session that a cluster with a given set of resources could afford.

These studies were performed in the ATLAS cluster located at Madison, with a PROOF sub-farm of 50 machines of 8 cores, 16 GB of RAM memory and a raid-5 storage setting of 8 disks, each with 750GB capacity.

A database in MySQL [79] was also designed to keep track of the information stored on each machine. It allowed to submit analysis (and also simulation) jobs where the input is stored. This saved time and avoided network traffic that normally generate data access conflicts, and in many cases bottle-necks. The required tests were done emulating different number of users or/and sessions, running analysis jobs on the same farm simultaneously. In Fig. 3.12 it can be seen how the system saturates, affecting the expected linear growth of the analysis rates, once the large number of cores required, start failing to access data on an effective manner. It also approaches its limits when a single session is started requiring more than 200 workers.

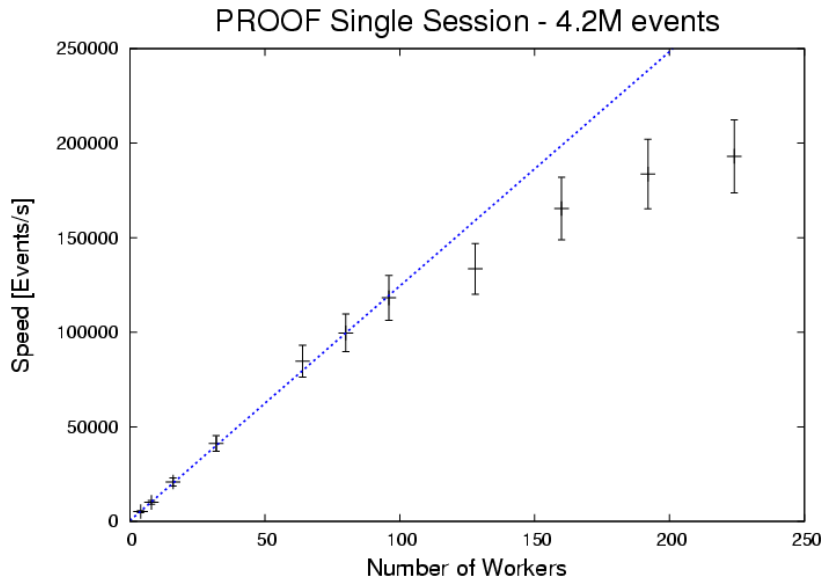


Figure 3.12: Analysis rate, in events per second for different number of workers assigned to a single session on the PROOF cluster

A similar situation is seen in Fig. 3.13 (Left), there is no gain in terms of performance, when 80 core per session instead of 60 are started in more than four simultaneous sessions. The ideal number of workers on a farm with the described resources is evaluated to be around 60. This even holds for the case of 8 users accessing the system simultaneously. These studies triggered several discussions aimed to investigated the feasibility of having a system that restricts (queue) the number of sessions/users allowing shorter analysis times; or to dynamically change the

3.4. Studies of Tier2/3 computing performance

allocated resources as function of the number of sessions used on a given time.

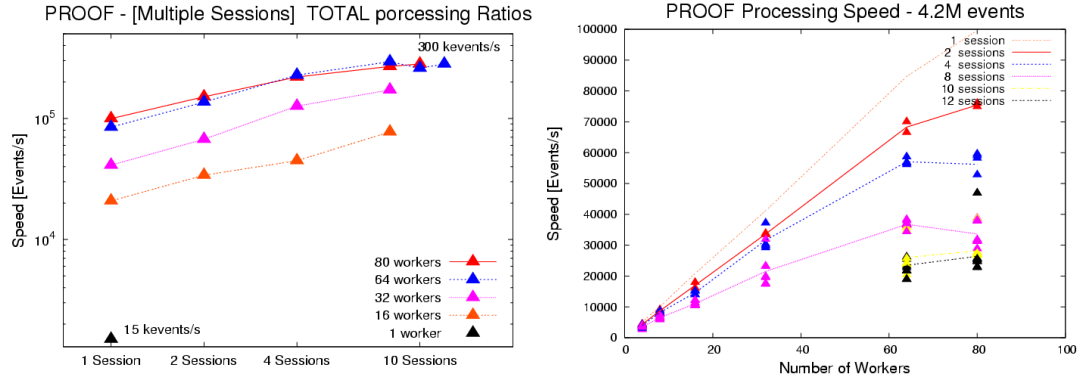


Figure 3.13: Left: Analysis rate, in events per second for different number of sessions started. Right: Event rates for number of worker settings of the PROOF cluster

Further checks showed that the disk access and data network sharing could be part of the reason that forbade a better performance. This was also supported by looking at Fig. 3.14, where it is shown how the network traffic peaks to ~ 2 GB/s when a series of sessions are started still keeping CPU requirements well below its limits.



Figure 3.14: Left: Network traffic when a set of consecutive session are started. Left: CPUs performance after several calls of PROOF sessions.

4 Monte Carlo Simulations



“Truth is much too complicated to allow anything but approximations.”

John von Neumann.

This chapter describes some of the different tools used in particle physics searches based on MC methods. Simulations are mainly used to estimate the expected reach of a particular search and are a stepping stone for detector design and calibration. The latter section of this chapter describe a method based on Parton Distribution Functions weights which allow to use already existing MC simulations in searches where a different centre-of-mass energy is assumed.

Monte Carlo simulations are vital to perform particle physics searches. They play a crucial role in the development and understanding of the detector, subsystems alignment and calibration.

Parton-level calculations of the targeted signal and the possible background processes need to be refined to take into account the detector acceptance effects. It is vital to consider the possibility of additional background contributions of process with slightly different signatures that could potentially emulate the signal signature when a certain object is misidentified. A typical example, in the final states with a pair of charged electrons and neutrinos like ($H \rightarrow WW \rightarrow e\bar{\nu}e\nu$ or $H \rightarrow ZZ \rightarrow e\bar{\nu}\nu\nu$). Is the SM production of W bosons together with a jet, the $W \rightarrow e\nu$ decay could provide the missing transverse energy required in the search, as well as one of the electrons. High P_T jets (hadronisation of quark/gluons) coming from HO corrections, or initial/final state radiations can be produced together with the weak boson. These jets could be misidentified as electrons completing the targeted $ee + E_T^{\text{miss}}$ signal signature.

Monte Carlo simulations with detailed description of detector geometry and magnetic fields have been used since the designed phase of the experiment's physics program. They played an

important role when needed to correctly plan and schedule the collider's program; optimising the sensitivity reach and the associated risk attached to the delivery of high energy and luminosity data.

4.1 Event generators and detector simulations

The simulation chain usually involve a matrix element calculation (typically at NLO or LO), where events containing 4-momenta information of the desired process are calculated. This information is then interfaced with a showering algorithm. Underlying event tunings dedicated to described the soft part of the $p-p$ interactions are also used [80, 81]. The modelling of the final-state radiation is performed with PHOTOS [82], and TAUOLA [83, 84] is used for the simulation of τ decays. The next step is to simulate the interaction of this “final state” particles with the detector materials, this is done with GEANT4 [85]. For this purpose a detailed description of the material composition and geometry, together with the magnetic fields are required [86]. The simulation of simultaneous collisions happening in the same bunch crossing is known as “pileup”. Since studies of sensitivity reach shown in Chap. 5 were intended for the first few hundred pb^{-1} , and up to 1 fb^{-1} of data, pileup was only included in the latter versions of MC simulations, used here for the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ search. Since the ATLAS detector has a very complex geometry, with components like its accordion-shaped LAr electromagnetic calorimeter, parametrisations have been also used to reduced the CPU cycles required by the simulation and reconstruction of events. These are known as ATLAS fast simulations [87, 88] (Atlfast). The results shown on this document used fully simulated signal and nominal background samples. Fast simulations were primarily used for studies involving systematic uncertainties, multivariate studies and template fits where very large event statistics are needed.

Simulations done at different times assumed different scenarios of $\sqrt{s}$ (14, 10, and 7 TeV). All simulated background samples are scaled to the highest available precision calculations for the relevant process. An overview of the relevant predictions and their uncertainties is given in Ref. [89]. The physics processes considered in the searches documented in Chap. 5 were simulated with a variety of programs:

- $gg \rightarrow H$ signal. For the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, MC@NLO [90] interfaced with JIMMY [91] was used. In the 4 leptons searches the PYTHIA LO generator was used. In all cases with full simulation of the ATLAS detector. Cross-sections are taken from the estimations described in Chap. 2. The optimisation study described in Appendix A.7.3 was performed using a set of signal samples generated with PYTHIA and simulated with Atlfast-I. In the case of the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ search a newer generator was used. The POWHEG [92, 93] event generator interfaced with PYTHIA [94] for the model of parton showers. The Higgs boson P_T spectrum in the gluon fusion process is reweighted to the calculation of Ref. [95], which provides QCD corrections up to NLO and QCD soft-gluon resummations up to NNLL.

- VBF $qq \rightarrow Hqq$ signal. It was modelled using HERWIG [96]. Underlying multiple parton scattering events are simulated with the help of the JIMMY package. For the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ search, POWHEG was also used for the VBF processes.
- Continuum $qq \rightarrow WW$ production. This is the dominant background in the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ analysis; It is modelled using MC@NLO, and the detector is simulated using Atlfast-I, Atlfast-II, and full simulation. It is worth noting that the Atlfast-I and Atlfast-II samples include a two-lepton filter cut, while the full simulation samples include only a one-lepton filter. There is therefore a small contribution from τ jets faking electrons which is present in full simulation but not in fast simulation. Section 6.2.5 discusses the Q^2 scale uncertainty in the background normalisation procedure; this calculation is based on a set of samples generated with the factorisation Q_{fac} and renormalisation Q_{ren} scales altered by factors of 8. The convention used throughout this thesis is that:

scale choice 1 corresponds to: $Q_{fac} \rightarrow 8Q_{fac}$ and $Q_{ren} \rightarrow Q_{ren}/8$;

scale choice 2 corresponds to: $Q_{fac} \rightarrow Q_{fac}/8$ and $Q_{ren} \rightarrow 8Q_{ren}$;

scale choice 3 corresponds to: $Q_{fac} \rightarrow 8Q_{fac}$ and $Q_{ren} \rightarrow 8Q_{ren}$;

and scale choice 4 corresponds to: $Q_{fac} \rightarrow Q_{fac}/8$ and $Q_{ren} \rightarrow Q_{ren}/8$.

- $gg \rightarrow WW$. This is a higher-order correction to $qq \rightarrow WW$ production; however, it cannot be neglected because the gluon luminosity is expected to be larger than the quark luminosity at LHC. This is modelled using GG2WW [97] hadronised with HERWIG; the detector is modelled using Atlfast-I, Atlfast-II, and full simulation. Fast simulation samples have been generated using the same set of altered Q^2 scale choices as the $qq \rightarrow WW$ background.
- $qq \rightarrow ZZ$. It is the dominant background in the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ and $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ searches. It is simulated with MC@NLO as was done with SM WW production. Since the MC@NLO does not describe off-shell Z in the diboson final state PYTHIA is used in the case of the 4 charged lepton search. In the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel, the PYTHIA sample is also used to obtain a systematic uncertainty on the description of the ZZ shape.
- WZ . It is a sub-leading background for most of the signal processes targeted on these searches. It was modelled using MC@NLO.
- $t\bar{t}$ and Wt . These backgrounds are modelled using MC@NLO and ACERMC respectively, and simulated using Atlfast-II and full simulation. For systematic uncertainties, and for the optimisation studies presented in Appendix A.7.3, privately produced Atlfast-I and Atlfast-II samples have been used. These samples include spin correlations in the top decay system. Theoretical issues surrounding the relative contribution of Wt and non-resonant $WWbb$ were studied using a set of samples generated with MADEVENT.

- $W+X$, where a jet is misidentified as an electron or a non-isolated lepton from a b decay is present. This process has been simulated using PYTHIA, and the response of the detector is modelled using full simulation. In addition, the contribution from Wbb events has been included using ALPGEN [98] interfaced with HERWIG for parton showers; this process is studied in full simulation.
- $Z/\gamma \rightarrow \ell\ell$. This background has been simulated using PYTHIA, and the detector is modelled using full simulation and Atfast-II. Since the description of the missing transverse energy is a crucial component for the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}+\text{jets}$ and for the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ searches, a fully simulated sample using ALPGEN was used.
- $\gamma+\text{jets}$. Although not a background in the signal region, it does enter into the analysis in the photon plus jet control sample discussed in Section 6.2.6 of the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ analyses. This process is generated using PYTHIA, and the detector response is modelled with full simulation.
- QCD multijets. The presently available MC statistics are not sufficient to compute a meaningful cross-section for this background in the signal region, but it is possible to study this as a background to the photon plus jet control sample. This background is modelled using PYTHIA and full simulation.
- $b\bar{b}$. This background is modelled using a privately produced sample generated with PYTHIA and simulated using Atfast-II. As will be seen for the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ analysis, in Sec. 6.2, the selection cuts exclude almost all of the available MC events. However, it is nonetheless important to normalise this background using data, since some studies have indicated that the acceptance is much larger than is suggested by the current MC sample [99].

These samples are all based on the ATLAS reconstruction and analysis software Athena [100]. Releases 14.2.25 and 14.5.0. were used for studies involving sensitivity reach, and 17.0.1 for the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ search.

4.2 Parton Distribution Function Reweighting

The schedule of the LHC has evolved as time has passed. Plans to perform collisions at the designed centre-of-mass energy of 14 TeV have been delayed to ensure the health and reliability of the accelerator. A new analysis campaign to update and further complete the expectations published in Ref. [27] started as soon as the LHC team decided to increase the beam energy slower than initially planned. Since the beam conditions could vary in a wide range of $\sqrt{s}$, a formalism that allow the re-weighting of existing MC based on PDF information was used. This is an approximated method that avoided the very time consuming re-simulation of all the physics processes.

The data-taking scenario used as a baseline for the 10 TeV analyses described in Sec. 6.2 consists of 200 pb^{-1} of integrated luminosity. However, at the time these studies were finalised, it was then expected that the data-taking period of 2010-2011 was going to consist primarily of collisions at a lower centre-of-mass energy of 7 TeV, with an integrated luminosity as large as 1 fb^{-1} .

Cross-sections for the 7 TeV running scenario have been estimated based on the existing 10 TeV MC samples using event-by-event PDF reweighting [101]. In general, the predicted cross-sections reported by a MC generator are computed according to

$$\sigma_{\text{Hadronic}} = \int f_1(x_1, \mu_F) f_2(x_2, \mu_F) \sigma_{\text{Partonic}}(p_1, p_2, \mu_F, \Pi) dx_1 dx_2 d\Pi \quad (4.1)$$

where x_1 and x_2 are the longitudinal momentum fractions carried by the partons, p_1 and p_2 are the actual momenta of the incident partons, μ_F is the factorisation scale of the event, and Π denotes the available phase space for the final state. The integral is evaluated by randomly sampling the phase space of the initial and final state, computing the integrand for each point, and taking a suitably weighted sum over the results.

The reweighting procedure is based on the observation that the integrand for the cross-section at a different centre-of-mass energy is essentially the same, but with x_1 and x_2 , and hence f_1 and f_2 replaced by values appropriate for the new centre-of-mass energy. In particular, one can write

$$\sigma'_{\text{Hadronic}} = \int R f_1(x_1, \mu_F) f_2(x_2, \mu_F) \sigma_{\text{Partonic}}(p_1, p_2, \mu_F, \Pi) dx_1 dx_2 d\Pi \quad (4.2)$$

where

$$R = \frac{f'_1(x'_1, \mu_F) f'_2(x'_2, \mu_F)}{f_1(x_1, \mu_F) f_2(x_2, \mu_F)} \quad (4.3)$$

and x'_1 and x'_2 are the momentum fractions (at the new centre-of-mass energy) carried by partons with the same momenta as partons which carry momentum fractions x_1 and x_2 at the old centre-of-mass energy. In the calculation of the weight R , the QCD scale used is the same one recorded by the generator in the HepMC PDFInfo object. In the case of generators which produce weighted events (MC@NLO, for example), the generator event weight is multiplied by the reweighting factor R . Thus, the cross-section at the new centre-of-mass energy is just a differently weighted sum based on the same fully-simulated or fast-simulated MC events. Note, however, that for MC samples where a generator-level filter has been applied, the filter efficiency is assumed to be the same at 7 TeV and 10 TeV. For most samples used in the analyses, the filters, if any are present, typically require the presence of one or two leptons in the final state. One would not expect the efficiency of such a cut to depend strongly on the centre-of-mass energy.

This method reproduces both the normalisation and parton-level kinematics at the new

Process	$\sigma_{7\text{TeV}}/\sigma_{10\text{TeV}}$	Mean Reweight	Discrepancy
W^+W^-	0.597	0.596 - 0.599	+0.2%
$t\bar{t}$	0.397	0.371	-6%
Wt	0.403	0.385	-4%
Z	0.668	0.672	+0.7%
W	0.690	0.691	+0.2%
$gg \rightarrow H$ (160)	0.502	0.486	-3%
$qq \rightarrow qqH$ (160)	0.502	0.482	-4%

Table 4.1: A comparison between the ratio of cross-sections at 7 TeV and 10 TeV as predicted by parton-level tools (“ $\sigma_{7\text{TeV}}/\sigma_{10\text{TeV}}$ ”) and using PDF reweighting (“Mean Reweight”).

centre-of-mass energy, but the parametrisation of the underlying event is still the one that was present in the 10 TeV samples. For the purposes of the present analysis, the difference in the underlying event parametrisation is not expected to be important. Table 4.1 shows a comparison of the ratio of cross-sections at 7 TeV and 10 TeV using parton-level calculations, and those obtained by the PDF reweighting method described above. The PDF reweighting method gives a cross-section that is correct to within a few percent. It is worth noting that, for the signal processes, the changes in cross-section reported here are consistent with the results described in Chap. 2; the ratio of the cross-sections give $\sigma_{7\text{TeV}}/\sigma_{10\text{TeV}}=0.509$ for $gg \rightarrow H$ and 0.499 for $qq \rightarrow H$.

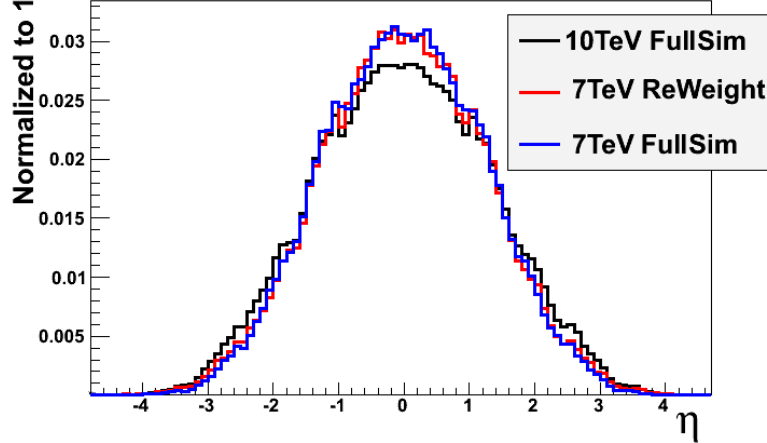


Figure 4.1: The pseudorapidity distribution of the leading jet in QCD dijet events at 10 TeV (black) and at 7 TeV using PDF reweighting (red) and using a dedicated, fully simulated sample of MC events generated with a centre-of-mass energy of 7 TeV and using the same PDF set as the 10 TeV sample (blue).

Figure 4.1 shows an example distribution comparing the shape of the leading jet pseudorapidity distribution at 7 TeV and 10 TeV. Generally, the kinematic distributions at 7 TeV are not very different from those at 10 TeV. Although it is not an extremely important variable

for this analysis, the pseudorapidity of the leading jet was chosen as an example because the change in its distribution when the centre-of-mass energy is lowered is more pronounced than the corresponding change for many other variables. The figure shows that the distributions reweighted to 7 TeV agree with the prediction of MC generated with a centre-of-mass energy of 7 TeV in cases where the kinematics do depend on $\sqrt{s}$. Further examples of validation distributions, as well as some details regarding an earlier reweight of MC simulation samples from 14 TeV to 10 TeV in the scope of the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ channel are shown in Appendix A.2

5 Higgs boson searches



“We have to remember that what we observe is not nature herself, but nature exposed to our method of questioning.”

Werner Heisenberg.

This chapter presents the Higgs boson searches in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay mode using $\int \mathcal{L} dt = 4.7 \text{ fb}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ real data. The latter section, gives a short summary of the combination of the different SM Higgs boson searches performed by the ATLAS collaboration.

The decay of the SM Higgs boson particle into a pair of weak bosons is the most powerful decay mode for m_H hypotheses larger than $\sim 140 \text{ GeV}$.

Three decay channels involving fully leptonic decay of the W and Z bosons are studied

- $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$
- $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$
- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$

here ℓ corresponds to e, μ ¹. These three studies were performed at different times.

The 4 lepton search is known as the golden mode [27] due to its remarkably clean and almost background free signature. The first part of Chap. 6 shows results performed as soon as it was

¹Effectively the leptonic decay of the τ leptons ($\tau \rightarrow \ell \nu_\ell \nu_\tau$) contributes to the final state tagged on these searches.

suggested that the bulk of the initial LHC data was not going to be delivered at the designed $\sqrt{s} = 14$ TeV. This studies were the first to quote the sensitivity reach of the ATLAS detector in the 4ℓ channel under such conditions.

Soon after, an effort started to redesign the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ [27, 102–104] analysis. It was known since some time, to be the most powerful yet challenging of the SM Higgs boson channels in the region close to the WW mass. Among the new different implementations, there were, a re-optimisation of the object selection, the definition of more robust and better control regions to measure backgrounds directly from data, and most important, the completion of the full jet multiplicities this analysis was divided on. The latter sections of Chap. 6 will present details of this analysis, as well as sensitivity prospects evaluated under different detector calibration and energy beam conditions.

At the time data arrived, efforts were directed to the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ searches. Thanks to the larger branching fraction of the $Z \rightarrow \nu \nu$ compared to $Z \rightarrow \ell \ell$, the newly designed $\ell \ell \nu \nu$ channel became the most sensitive channel for very heavy Higgs boson searches ($m_H \sim 400$ GeV). This study was initially targeted to search for a heavy Higgs boson in the range between 200–600 GeV; but given that the $\int \mathcal{L} dt = 4.7 \text{ fb}^{-1}$ of integrated luminosity allowed to start probing an even heavier ZZ resonance, the search was extended imposing a limit on a production cross-section rather than on the SM Higgs boson prediction, to cover regions up to 900 GeV in a more heavy Higgs-model independent way. This chapter presents the details and results of this search.

The latter section of this chapter describes the results produced by the ATLAS Collaboration. Results were updated for all its SM Higgs boson searches using the data collected during 2011. In the low mass region $m_H \in [110 - 150]$ GeV the include channels were: $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $VH \rightarrow b\bar{b}$ (only up to 130 GeV); two analyses cover the full wide search range [110 – 600] GeV: $H \rightarrow ZZ \rightarrow 4\ell$ and the $H \rightarrow WW \rightarrow \ell \nu \ell \nu$; and three analysis are performed in the high m_H region [200 – 600] GeV: $H \rightarrow ZZ \rightarrow \ell \ell \nu \nu$, $H \rightarrow ZZ \rightarrow \ell \ell q q$ and $H \rightarrow WW \rightarrow \ell \nu q q$ (which starts at 320 GeV). The statistical combination of this channels allowed to put constraints on the existence of the SM Higgs boson, ruling out its existence in a very wide range. In the unexcluded low m_H region, a 2.6σ (local significance) excess is observed compatible with the presence of a ~ 126 GeV SM Higgs boson.

5.1 $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$: Data analysis with 4.7 fb^{-1}

The $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay channel (Feynman diagram shown in Fig. 6.1) offers a substantial branching fraction in combination with a good separation from potential background processes owing to the high transverse momentum, P_T , of the electron or muon pair from the leptonic Z decay and the high missing transverse momentum, E_T^{miss} , from the Z decaying to neutrinos.

Simultaneously with the writing of this thesis, the results presented on this chapter with the exception of the high m_H extension were submitted to the Physics Letters B. Journal [105]. Earlier results in this channel, published in Ref. [106] using 1.04 fb^{-1} were subsequently updated in Ref. [107] with 2.05 fb^{-1} and exclude at the 95% confidence level the presence of a SM Higgs boson in the range $310 < m_H < 470 \text{ GeV}$. The most recent CMS analysis [108] in this channel based on 4.6 fb^{-1} excluded $270 < m_H < 440 \text{ GeV}$.

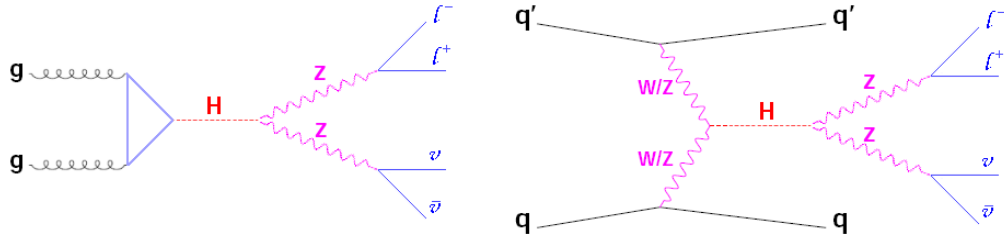


Figure 5.1: Feynman diagram for Higgs boson production through the gluon-gluon fusion and VBF production mechanisms, with the respective decay into two opposite charged leptons and a neutrino pair from Z decays.

The data sample considered in the search presented in this section was recorded by the ATLAS experiment during the 2011 LHC run at a centre-of-mass energy $\sqrt{s} = 7 \text{ TeV}$. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were operational, is 4.7 fb^{-1} with an uncertainty of 3.9% [109, 110].

5.1.1 Data and simulation samples

As described in Chap. 4, the MC simulation signal samples are modelled using the POWHEG event generator, which includes matrix elements for the gluon fusion and VBF production mechanisms of the Higgs boson up NLO. $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, $H \rightarrow ZZ \rightarrow \ell^+ \ell^- q \bar{q}$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ samples are also used with the same generators as for the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ samples. These channels together with the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \tau^+ \tau^-$ final state also present in the nominal signal sample contribute to the signal yield and are considered as part of the signal. In particular, $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ decays contribute as much as 70% to the signal expectation after the full selection for $m_H = 200 \text{ GeV}$, decreasing to 13% at $m_H = 300 \text{ GeV}$, and to less than 4.5% for Higgs boson masses larger than 400 GeV. Orthogonality

of the analysis with respect to other ATLAS Higgs boson searches [111–113] is ensured through mutually exclusive selection requirements on the dilepton invariant mass, the number of leptons and the missing transverse momentum in the event. The $WW \rightarrow \ell \nu \ell \nu$ channel veto events if the invariant mass of the dilepton system is close to the Z boson mass (Sec. 6.2); the 4ℓ analysis has an explicitly requirement on the number of leptons (Sec. 6.1), and the $ZZ \rightarrow \ell \ell qq$ search cuts away events with large E_T^{miss} values. Table 5.1 gives further details of the cross fed of the different channels for several Higgs boson masses.

Table 5.1: The number of events from different Higgs boson decay modes relative to the total number of signal events, after the full $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ selection. In all signal samples τ leptons are included.

Sample	$H \rightarrow ZZ \rightarrow ll\nu\nu$	$H \rightarrow ZZ \rightarrow llll$	$H \rightarrow ZZ \rightarrow llqq$	$H \rightarrow WW \rightarrow l\nu l\nu$
200	25.5%	0.4%	0.0%	74.1%
300	87.0%	0.8%	0.0%	12.2%
400	94.5%	1.0%	0.0%	4.5%
500	96.9%	0.9%	0.0%	2.2%
600	97.4%	0.8%	0.0%	1.8%
700	97.7%	0.8%	0.0%	1.5%

The Higgs boson production cross-sections and decay branching ratios as well as their uncertainties, are described in Chap. 2.

Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. The MC samples are reweighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data.

Data used for the search in the muon channels are collected primarily using single muon triggers with P_T thresholds of 18 GeV, while in the electron case a logical OR between single electron triggers with thresholds varying from 20 to 22 GeV and a dielectron trigger with a P_T threshold of 12 GeV is used. The expected trigger efficiency is close to 100% in the electron channel and between 94% and 97% in the muon channel for signal events passing the full selection cuts described below.

During the course of the 2011 data taking the average number pileup interactions increased due to increased beam currents and improved beam focusing. This changed the average number of interactions per bunch crossing at the start of a fill, from about 6 in the earlier periods to about 15 in the later periods. The missing transverse momentum resolution is affected by the level of pile-up, resulting in a significant change in the signal to background ratio between the earlier and the later periods. To retain the best sensitivity the search is therefore split between the earlier (2.3 fb^{-1}) and the latter (2.4 fb^{-1}) periods, hereafter referred to as the “low pile-up data” and the “high pile-up data”, respectively. The selection is unaltered between the periods.

5.1.2 Lepton identification and event selection

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated to ID tracks. The electron candidates must satisfy a set of ATLAS “medium” identification criteria [114] that require the shower profiles to be consistent with those expected for electromagnetic showers and a well-reconstructed ID track pointing to the corresponding cluster. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point.

For muons, the STACO ATLAS reconstruction algorithm was used. Muons are identified by reconstructing tracks in the muon spectrometer. These tracks are then extrapolated back to the beam line to find a matching ID track.

Jets are used in this analysis to reject backgrounds from events with heavy quark decays or from events with fake missing transverse momentum E_T^{miss} due to mis-measured jets. For this purpose jets are reconstructed from clusters of energy deposits in the calorimeters using the anti- k_t algorithm [115] with a radius parameter $R = 0.4$.

The kinematic pre-selection of the different objects is:

- **electrons**
 - $p_T > 20 \text{ GeV}$
 - $|\eta| < 2.47$.
 - ATLAS “Medium” identification.
 - Track isolation: $\sum \text{Track}_{p_T} / e_{p_T} < 0.10$ in a cone $\Delta R < 0.2$ around the lepton direction
- **muons**
 - $p_T > 20 \text{ GeV}$
 - $|\eta| < 2.5$.
 - STACO
 - Track isolation: $\sum \text{Track}_{p_T} / e_{p_T} < 0.10$ in a cone $\Delta R < 0.2$ around the lepton direction
- **jets**
 - $p_T > 25 \text{ GeV}$
 - $|\eta| < 2.5$.
 - anti- k_t algorithm, with cone of 0.4

An overlap removal between leptons and jets within a distance $\Delta R < 0.4$ is also performed.

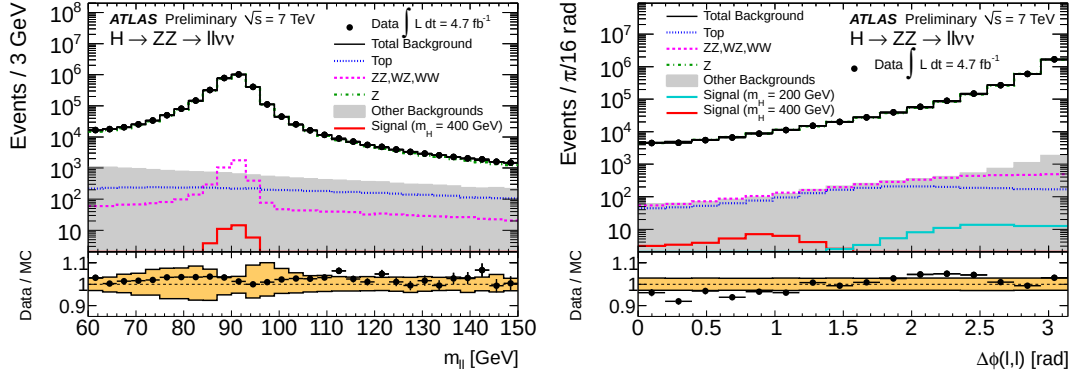


Figure 5.2: Left: The dilepton invariant mass distribution for events with exactly two oppositely charged electrons or muons. Right: The azimuthal separation between leptons for events with a lepton pair with invariant mass satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV. The inset at the bottom of the figures shows the ratio between the data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties.

The missing transverse momentum is measured as the (negative) vectorial sum of the transverse momenta of all cells in the calorimeters within $|\eta| < 4.8$, calibrated appropriately based on their identification as electrons, photons, taus, jets or unassociated calorimeter cells, and all selected muons in the event [116]. Calorimeter deposits associated with muons are subtracted to avoid double counting.

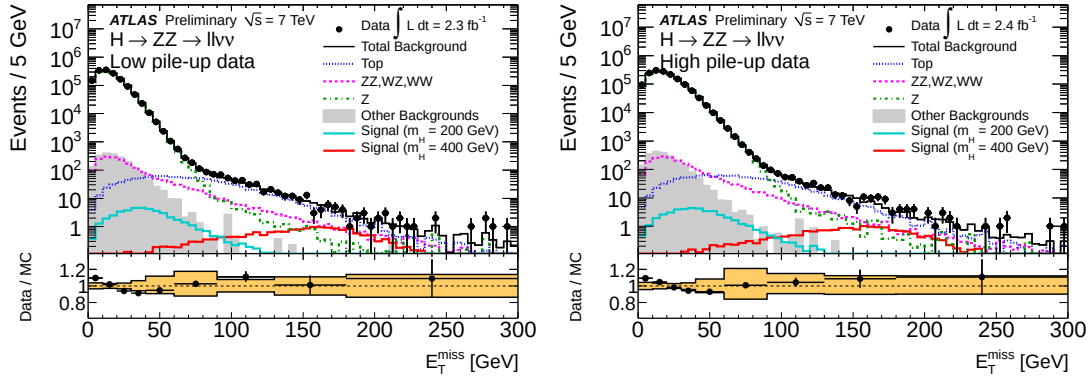


Figure 5.3: The E_T^{miss} distributions for events with exactly two oppositely charged electrons or muons satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV, for the low pile-up (Left) and the high pile-up data (Right). The insets at the bottom show the ratio between data and the combined background expectations as well as a band corresponding to the combined systematic uncertainties.

- **Reconstructed primary vertex:** Events are required to contain a reconstructed primary vertex formed from at least three tracks and exactly two oppositely charged electrons or muons, consistent with having originated from the primary vertex.

- Exactly two good leptons, compatible with a Z boson decay:** Events containing a third lepton as defined above with a loosened P_T requirement of at least 10 GeV are also rejected. The dilepton mass distribution is shown in Fig. 5.2 (Left). Inclusive Z boson production is the dominant background at this stage of the analysis. To suppress backgrounds from top, inclusive W , and multijet production the dilepton invariant mass, $m_{\ell\ell}$, is required to satisfy $|m_Z - m_{\ell\ell}| < 15 \text{ GeV}$.
 - Veto event containing b -jets:** To reduce the background from top quark production, events with one or more b -tagged jets are rejected. The b -tagging is based on a multivariate algorithm which uses information from both the impact parameter with respect to the primary vertex of tracks associated to the jet and the presence of displaced secondary vertices associated to the jet's tracks. In particular for the b -tag veto, jets with a loosened P_T threshold of 20 GeV and $|\eta| < 2.5$ are considered. The procedure achieves an efficiency of about 85% for identifying real b -jets [117] in inclusive top pair events.
 - Missing transverse momentum:** To exploit the mass dependent kinematic features of $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ production, the search is subdivided into a low Higgs boson mass ($m_H < 280 \text{ GeV}$) and a high Higgs boson mass ($m_H \geq 280 \text{ GeV}$) search region, where dedicated cuts are applied to two important discriminating variables used to reduce the background contributions: E_T^{miss} and the azimuthal angle between the two leptons, $\Delta\phi(\ell, \ell)$. Figures 5.2 (Right) and 5.3 show the distributions of these variables after the application of the cut on $m_{\ell\ell}$.
- Since inclusive Z production gives rise to a steeply falling E_T^{miss} distribution, systematic uncertainties on the E_T^{miss} reconstruction are particularly important in order to estimate this background correctly.
- The dominant contribution to the E_T^{miss} uncertainty comes from the knowledge of the jet energy scale. A degradation of the E_T^{miss} resolution is observed in the data taken during the periods with a larger average number of interactions per bunch crossing, as is illustrated in Fig. 5.3. This increases in particular the background from inclusive Z production in the high pile-up periods mostly in the low mass search region.
- Figure 5.3 shows that an agreement within systematic uncertainties is observed between data and the combined background expectation. In the low m_H region, events are required to satisfy $E_T^{\text{miss}} > 66 \text{ GeV}$, whilst in the high m_H region the requirement is $E_T^{\text{miss}} > 82 \text{ GeV}$. These cuts reduce significantly the backgrounds from processes with no or modest genuine missing transverse momentum originating from unobserved neutrinos.
- Opening angle between leptons in the azimuthal plane:** The boost of the Z bosons originating from a Higgs boson decay increases with m_H , thus reducing the expected opening angle between the leptons. In the low m_H region this boost is expected to be modest and a cut $1 < \Delta\phi(\ell, \ell) < 2.64$ is applied. In the high m_H region an upper bound $\Delta\phi(\ell, \ell) < 2.25$ is required.

- **Transverse direction of reconstructed Z boson and $\vec{p}_T^{\text{miss}}$:** In the high m_H region, events are also rejected if the azimuthal angle between the missing transverse momentum vector and the direction of the $Z \rightarrow \ell^+ \ell^-$ boson candidate is $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\ell\ell}) < 1$.
- **Angle of reconstructed jet and direction of E_T^{miss} vector:** Finally, to further reduce the background from events with fake E_T^{miss} due to mis-measured jets, events are rejected if the azimuthal angle between the missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, and its nearest jet in the event satisfies $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 1.5$ for the low m_H search and $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 0.5$ for the high m_H region.

The efficiency of the event selection is very similar in the electron and muon channels, ranging from 3.1% for $m_H = 200$ GeV to about 43% for $m_H = 600$ GeV.

5.1.3 Background normalisation and control regions

Standard Model pair production of Z bosons has a final state identical to the signal, and is therefore expected to survive most of the applied selection criteria and form a continuum in the transverse mass distribution (defined below). The normalisation for this background is obtained from a calculation including next-to-leading order terms [118] with an additional 6% term to account for missing quark-box diagrams ($gg \rightarrow ZZ$) [119]. An 11% normalisation uncertainty is assigned to this background, estimated from scale, PDF [57] and model uncertainties. The shape for the ZZ background is taken from the MC simulation with a systematic uncertainty given by the shape prediction when an alternative, PYTHIA, event generator is used. WW and WZ backgrounds are normalised in a similar way. For the WZ background the normalisation is verified using a control sample in which the presence of exactly three leptons is required, where the minimum P_T for the third lepton is 10 GeV. Figure 5.4 (Top Left) shows the E_T^{miss} distribution in this control region, which is dominated by WZ background and is well modelled by the MC simulations.

The background from top events is taken from the MC prediction. This prediction is verified to agree with data, within systematic uncertainties, in two independent control samples: the first uses the dilepton mass sideband and requires at least one identified b -jet (Fig. 5.4 Top Right), while the second selects events containing electron-muon pairs (Fig. 5.4 Bottom Left).

Additional backgrounds can arise from multijet events or inclusive W production due to heavy flavour decays or jets misidentified as leptons. The normalisation of the inclusive W background in this search is obtained from a control sample of events with a like-sign electron-electron or electron-muon pair in the sidebands of the dilepton mass distribution and with no b -tagged jets. Figure 5.4 (Bottom Right) shows the E_T^{miss} distribution following this procedure. At high E_T^{miss} this distribution is dominated by the inclusive W background.

The multijet background in the electron channel is determined using a data sample based on a loosened electron selection, and is thus dominated by jets; this sample is scaled to describe

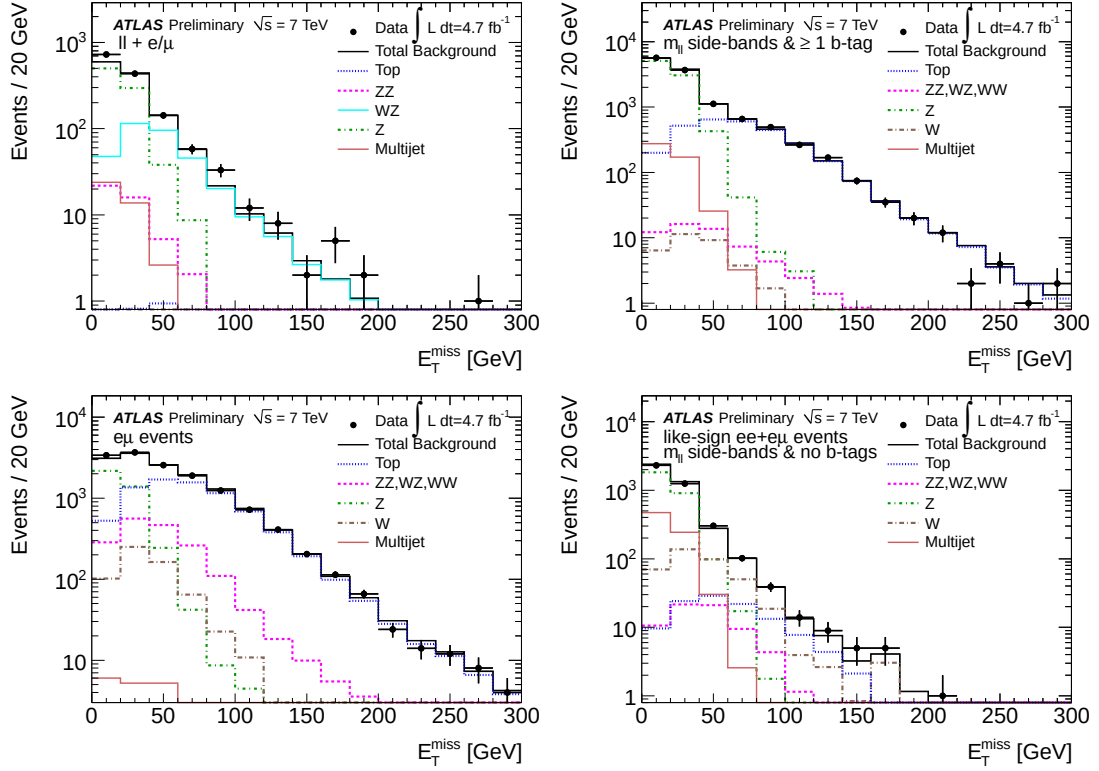


Figure 5.4: The E_T^{miss} distribution in the different control regions: Top Left: WZ control region with events containing exactly three leptons. Top Right: top control region populated with events containing at least one b -jet and a lepton pair in the sidebands of dilepton mass distribution. Bottom Left: Second top control region populated with top background with events with an e/μ pair. Bottom Right: Inclusive W boson control region populated with events with no b -tagged jets and a same-sign ee or $e\mu$ pair in the sidebands of dilepton mass distribution.

the tails of the $m_{\ell\ell}$ distribution. In the muon channel, the background from heavy flavour decays is studied using simulation, whereas other muon sources from multijet events are constrained using a sample of like-sign muon pairs in data. In both cases the background is found to be negligible.

The background from inclusive Z production is verified in a control region populated with events rejected by the $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ cut after the E_T^{miss} requirement. The full $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ distribution is shown in Fig. 5.5. At low $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$, where inclusive Z background dominates, agreement within uncertainties is observed between the data and the expected backgrounds.

The signal efficiencies and overall background expectations are similar in the electron and the muon channels (The separated cutflow tables are shown in Appendix A.4). The numbers of candidate $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ events selected in data and the expected yields from signal and background processes are shown in Table 5.2.

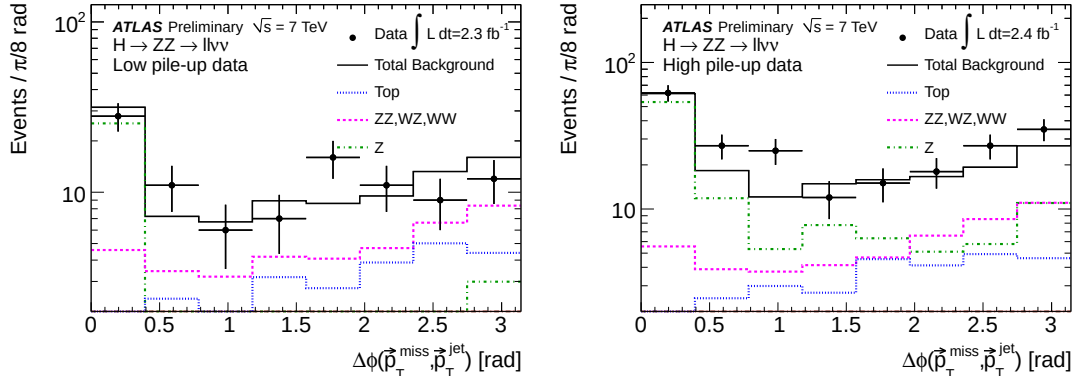


Figure 5.5: The azimuthal separation between the missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$ and its nearest jet in the event $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ after the E_T^{miss} requirement, for the high m_H search region. Left: low pile-up data. Right: high pile-up data.

Table 5.2: The expected number of background and signal events along with the observed numbers of candidates in the data, separated in the low and high m_H search regions and the low and high pile-up periods. The quoted uncertainties are statistical and systematic, respectively.

	low m_H search		high m_H search	
Source	Low pile-up data	High pile-up data	Low pile-up data	High pile-up data
Z	$40.1 \pm 5.0 \pm 7.9$	$264.7 \pm 12.7 \pm 67.3$	$0.8 \pm 0.3 \pm 0.8$	$11.6 \pm 2.1 \pm 2.9$
W	$4.6 \pm 2.2 \pm 4.6$	$5.8 \pm 1.8 \pm 5.8$	$1.5 \pm 0.8 \pm 1.5$	$2.2 \pm 1.3 \pm 2.2$
top	$23.2 \pm 1.3 \pm 5.4$	$27.9 \pm 1.3 \pm 5.3$	$16.0 \pm 1.1 \pm 4.0$	$17.2 \pm 1.0 \pm 3.9$
multijet	$1.1 \pm 0.2 \pm 0.5$	$1.1 \pm 0.2 \pm 0.6$	$0.1 \pm 0.1 \pm 0.0$	$0.1 \pm 0.1 \pm 0.0$
ZZ	$33.4 \pm 0.7 \pm 3.9$	$36.7 \pm 0.7 \pm 4.3$	$28.4 \pm 0.6 \pm 3.4$	$31.9 \pm 0.7 \pm 3.8$
WZ	$23.3 \pm 1.0 \pm 2.8$	$25.2 \pm 1.0 \pm 3.0$	$17.1 \pm 0.8 \pm 2.1$	$18.9 \pm 0.8 \pm 2.3$
WW	$25.5 \pm 0.8 \pm 3.0$	$32.4 \pm 0.9 \pm 3.8$	$9.4 \pm 0.5 \pm 1.1$	$13.3 \pm 0.5 \pm 1.6$
Total	$151.2 \pm 5.8 \pm 11.2$	$394.0 \pm 13.0 \pm 66.9$	$73.3 \pm 1.8 \pm 6.1$	$95.2 \pm 2.9 \pm 6.9$
Data	158	442	77	109
m_H [GeV]	Signal expectation			
200	$10.3 \pm 0.2 \pm 1.8$	$11.1 \pm 0.2 \pm 1.9$		
300			$16.4 \pm 0.3 \pm 2.9$	$17.5 \pm 0.3 \pm 3.1$
400			$14.4 \pm 0.2 \pm 2.5$	$15.4 \pm 0.2 \pm 2.7$
500			$6.2 \pm 0.1 \pm 1.1$	$6.5 \pm 0.1 \pm 1.1$
600			$2.7 \pm 0.0 \pm 0.5$	$2.9 \pm 0.0 \pm 0.5$

5.1.4 Systematic uncertainties

The systematic uncertainties applied in this search include experimental uncertainties related to the selection and calibration of electrons, muons and jets, which are also all explicitly propagated to the E_T^{miss} calculation. Uncertainties on the b -tagging efficiency as well as the light and charm jet mis-tagging rates are also applied.

Normalisation uncertainties for the signal (gluon fusion $^{+14\%}_{-10\%}$ and VBF 4%) and for the diboson backgrounds (11%) are obtained from theory [49]; uncertainties for the inclusive Z boson

production (2.5%), top quark production (9%), inclusive W boson production (100%) and multijet production in the electron channel (50%) are estimated from data.

For the signal an additional uncertainty is applied to account for the possible effect of theoretical uncertainties on the acceptance. This uncertainty is estimated from signal samples containing variations in the initial and final state-radiation modelling, the renormalisation and factorisation scales, as well as variations in the underlying event tune, which was changed from the default AUET2B [120] to PERUGIA2011 [80], both based on LHC data. An overall uncertainty of 8.4% (3.4%) is assigned in the low (high) mass search regions, obtained by the addition in quadrature of the largest deviations observed for each variation.

The luminosity uncertainty is 3.7% and 4.1% for the low and high pile-up data, respectively, based on the calibration described in Refs. [109, 110]. The total systematic uncertainty on the signal and on each of the background contributions can be seen in Table 5.2. In most cases the assigned normalisation uncertainties dominate the total systematic uncertainty, except for the inclusive Z background, for which the jet energy scale and resolution uncertainties dominate. In the low m_H search using the high pile-up data, the uncertainty on the inclusive Z background uncertainty dominates the overall uncertainty.

5.1.5 Results

After the event selection, the Higgs boson search is performed by looking for an excess of data over the SM background expectation in the transverse mass distribution of the selected $e e \nu \nu$ and $\mu \mu \nu \nu$ events. The transverse mass is calculated from the lepton pair and the $\vec{p}_T^{\text{miss}}$ vector as:

$$\left[m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2} \right]^2 - \left[\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}} \right]^2 \right] \quad (5.1)$$

Figure 5.6 shows the m_T distributions in the low (Top) and high (Centre and Bottom) m_H search regions with the expected signal for a Higgs boson mass of 200 GeV (Top) 400 GeV (Centre) and 600 GeV (Bottom). The low pile-up (Left) and high pile-up (Right) data are shown separately.

The number and distribution of candidate $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ events observed in the data agree with the expected backgrounds within the uncertainties. No indication of an excess is seen, with the smallest p_0 -value being 0.05 observed at $m_H=280$ GeV. Upper limits are set on the Higgs boson production cross-section relative to its predicted SM value as a function of m_H . The limits are extracted from a maximum likelihood fit to the m_T distribution following the CL_s modified Frequentist formalism [121] with the profile likelihood test statistic [122]. All systematic uncertainties are taken into account. Further details on the limit setting formalisms are given in Appendix A.3.

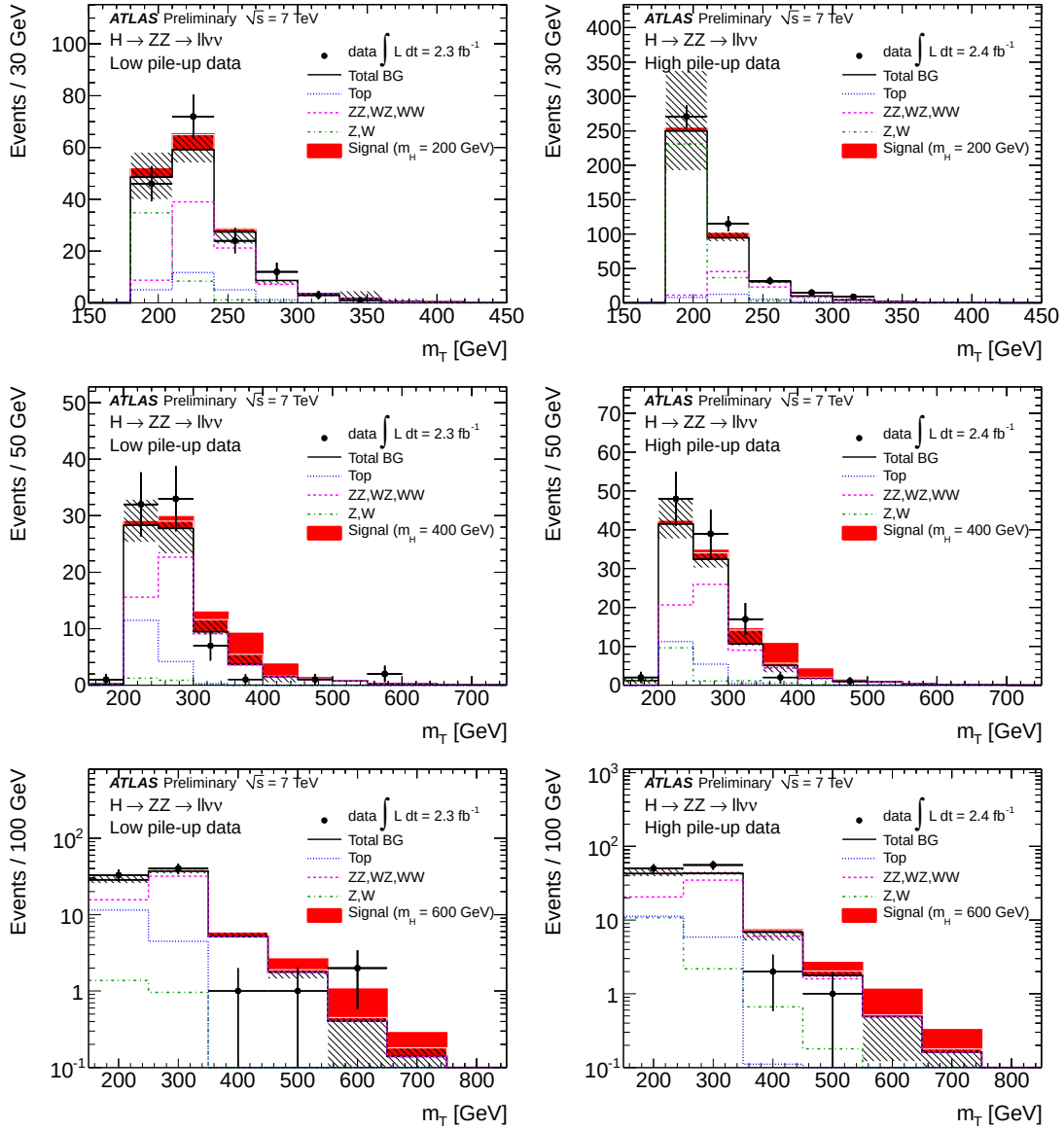


Figure 5.6: The transverse mass distribution of $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ candidates. Figures on the Top refer to the low m_H search region and figures on the Centre and Bottom to the high m_H search region. The top, centre and bottom figures show the expected signal for a Higgs boson with a mass of 200 GeV, 400 GeV and 600 GeV, respectively. Figures on the left correspond to the low pile-up data and figures on the right to the high pile-up data.

Figure 5.7 shows the expected and observed limits at the 95% confidence level. Fluctuations in the background can lead to better or worse observed limits compared to the SM prediction in the absence of a Higgs boson. The green and yellow bands indicate the expected sensitivity with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively. The mass range between 260 – 490 GeV is expected to be excluded while observation shows that a SM Higgs boson is excluded at the 95% confidence level in the range of 319 – 558 GeV.

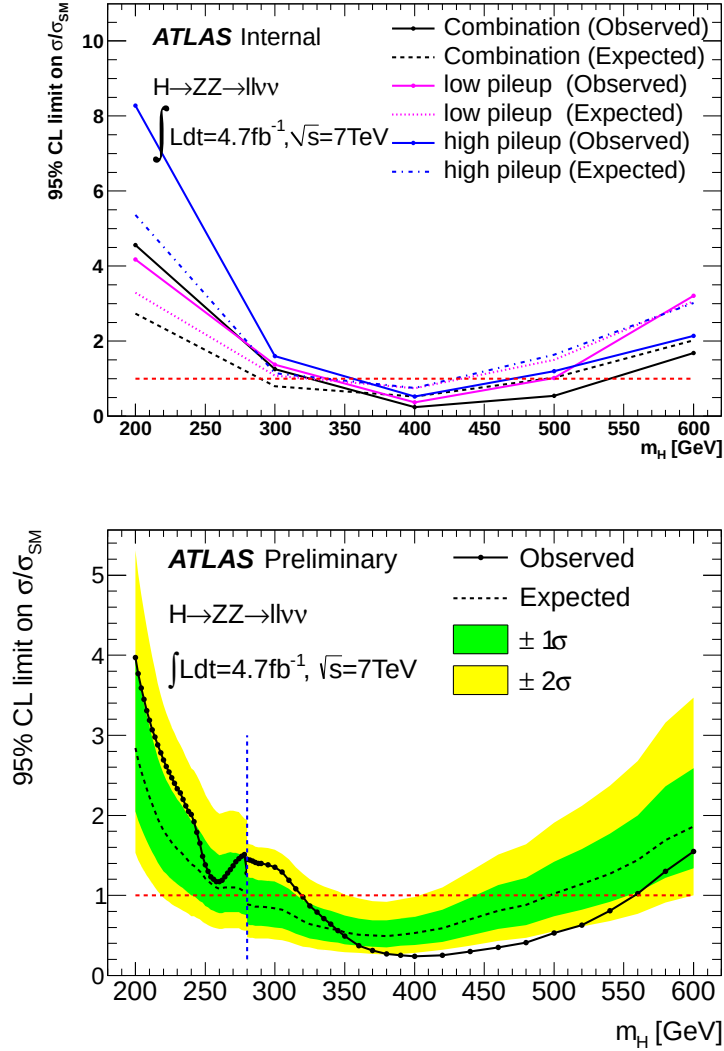


Figure 5.7: Observed and expected 95% confidence level upper limits on the Higgs boson production cross section divided by the SM prediction. Top: individual contributions of low and high pileup periods for selected m_H points in 100 GeV steps. Bottom: Combined result, together with the green and yellow bands which indicate the $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively, around the median sensitivity. The limits are based on 4.7 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$. The line at 280 GeV indicates the transition from the low m_H to the high m_H search region.

The Higgs boson cross-sections are calculated with a zero-width approximation. For the Higgs boson decay, an ad-hoc relativistic Breit-Wigner (BW) line shape is normally applied at the event-generator level. It has been suggested [57, 123–125] that effects related to off-shell Higgs boson production and interference with other SM processes may become sizable for the highest Higgs boson masses ($m_H > 400 \text{ GeV}$) considered in this search. Since the line shape effects becomes evident, when exploring higher masses, an acceptance systematic uncertainty for the gluon fusion production mechanism at $m_H > 400 \text{ GeV}$ was included. It was obtained by,

reweighting the lineshape to match a lineshape calculated in the complex pole estimation [126]. Currently, in the absence of a full lineshape calculation for the production mechanisms as well as a correct account of the interference with SM ZZ production, a conservative estimate of the possible size of such effects is included as a signal normalisation systematic uncertainty, following a parametrisation as a function of m_H : $1.5 \times m_H^3 [\text{TeV}]$ for $m_H \geq 300$ GeV [57] is included in the analysis.

This additional systematic uncertainty on the signal normalisation becomes too conservative for m_H larger than 600 GeV. With the current luminosity the LHC experiments could already explore a larger phase space. The various corrections needed for a heavy Higgs-like boson and their systematic uncertainties have not been completed at the time of writing this thesis². Nevertheless a limit on the excluded cross-section σ , rather than on the ratio of σ/σ_{SM} allows a more model independent result. It partially factorises the signal normalisation prior and its uncertainties. Figure 5.8 shows this result. The theory predictions on Fig 5.8, correspond to: on red, the nominal values used when no corrections for Higgs boson width nor interference effects are added (relativistic BW); on blue, the normalisation obtained by the full complex pole calculation [126] of the gluon fusion mechanism with the nominal (relativistic BW) addition of the VBF; and on brown the results obtained by the iHIXS calculation. Upper limits on the

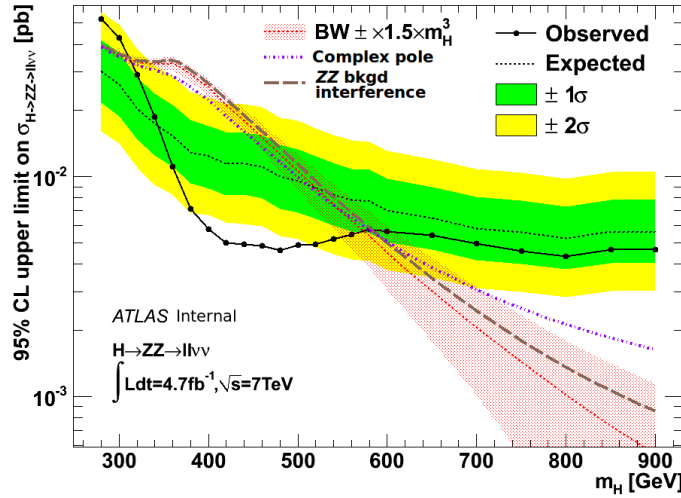


Figure 5.8: Observed and expected 95% confidence level upper limits on the Higgs-like boson production cross section. Theory predictions included the addition of the nominal values for VBF production. The respective corrections when interference (blue) or full lineshape calculation (blue) are display. The prediction with no extra Higgs boson width effects besides a relativistic Breit Wigner and an error as function of m_H^3 are also shown (red).

production cross section of a scalar Higgs-like boson decaying into a ZZ pair are presented up to m_H of 900 GeV.

²This is particularly true for the VBF production mechanism. As it can be seen on various figures in Chap. 2, at $m_H = 1$ TeV the VBF mechanism is as large as the gluon initiated process

5.2 Statistical combination of Higgs boson searches in ATLAS

The ATLAS Collaboration has updated all its Higgs boson searches using the complete data-set collected during 2011. It corresponds to an integrated luminosity ranging between 4.6 to 4.9 fb⁻¹ depending on the requirements of each channel in terms of subdetector quality needs. For example, the $H \rightarrow \gamma\gamma$ channel can use data taken when part of the muon spectrometer was not fully functional. Channels where a full set of objects are used, in particular those with missing transverse energy requirements typically need to use all of the subdetectors.

5.2.1 Channels combined

The channels considered on this combination are : $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $VH \rightarrow b\bar{b}$, $H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$, $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$, $H \rightarrow ZZ \rightarrow \ell\ell qq$ and $H \rightarrow WW \rightarrow \ell\nu qq$

The low mass channels can search for Higgs boson decays to $b\bar{b}$, $\gamma\gamma$, or $\tau\tau$. The m_H range they probe is between 110 and 130 for the associated production search with the subsequent decay of a $b\bar{b}$, and can be extended to $m_H < 150$ GeV in the case of the diphoton and tau pair searches. The medium mass region [150-200] GeV is covered by two channels, the $WW \rightarrow \ell\nu\ell\nu$ and the $ZZ \rightarrow 4\ell$. Since these two channels are sensitive through the whole searched mass spectrum [110-600] GeV, they also contribute to the low and higher mass searches. The high mass search in ATLAS, is also formed by the $ZZ \rightarrow \ell\ell\nu\nu$, $ZZ \rightarrow \ell\ell qq$ and $WW \rightarrow \ell\nu qq$ searches. These analyses search for a Higgs boson with a mass between 200 and 600 GeV, with the exception of the $\ell\nu qq$ analysis which is only feasible for masses larger than 320 GeV, where the overwhelming W +jets background can be controlled.

As shown for the searches studied on this document, to enhance sensitivity, channels are normally separated into subchannels. Below, some details of this categorisation for each of the analyses are given.

- $VH \rightarrow b\bar{b}$:

As it was shown in Chap. 2, the SM Higgs boson would prefer to decay onto different objects depending on its mass. In the low mass region, typically $m_H < 150$ GeV; the Higgs boson would predominately decay in a $b\bar{b}$ pair. This signature cannot be separated from the many orders-of-magnitude higher irreducible multijet background. To make this search possible, experimentalist tag Higgs boson events that are produced in association with a weak boson (As explain in Chap. 2). The decay of these weak bosons into leptons provide not only a strong discriminating power, but also the possibility to use this decay products to trigger the events. Three separate analysis are performed: The $ZH \rightarrow \ell\ell b\bar{b}$, the $WH \rightarrow \ell\nu b\bar{b}$ and the $WH \rightarrow \nu\nu b\bar{b}$. Thanks to the recoiling of the weak boson, signal events would tend to have a boost. For the channels with charged leptons, further discrimination is obtained by separating them into leptons flavours, and by binning on the W or Z transverse momentum. Details of these analyses can be found in Ref [127].

- $H \rightarrow \gamma\gamma$:

The photon energy resolution is different if they are directly measured, or reconstructed from ID converted objects; resolution also has a clear η : (barrel/endcap) dependency. The diphoton search can profit from these different detector features by separating the event candidates into different categories where different sensitivity is expected. The separation of events based on the momentum component of the diphoton system transverse to the thrust axis completes the nine different categories used in the $\gamma\gamma$ search. The diphoton invariant mass distribution is fitted, where the search of a peak with floating width and strength is performed for each m_H hypothesis. Details of this analysis can be found in Ref [128].

- $H \rightarrow \tau\tau$:

The τ decays determine the division of this analysis in three categories. When both τ leptons decay leptonically: $H \rightarrow \tau\tau \rightarrow \ell^+ \ell^- 4\nu$; when one of the τ leptons decay leptonically and the second hadronically: $H \rightarrow \tau\tau \rightarrow \ell 3\nu \tau_{had}$; and when both leptons hadronise in the calorimeters as tau-jets: $H \rightarrow \tau\tau \rightarrow \tau_{had} \tau_{had} 2\nu + \text{jet}$. Details of these analyses can be found in Ref [129].

- $H \rightarrow ZZ \rightarrow 4\ell$:

The analysis performed on the 2011 data is based on the cutbased analysis described in Sec. 6.1. Subtle improvements in terms of object definitions and a full set of control regions to ensure irreducible backgrounds are under control were added. Additionally, the categorisation by flavours is also done for the selected on-shell set, leaving four main categories, the $4e$, 4μ , $2e2\mu$ and the $2\mu2e$. Details of this analysis on data can also be found in Ref [112].

- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$:

Besides some changes of the control region definitions, and some refined definition for object selections, the bulk of the WW dilepton analysis is based on the studies shown in Sec. 6.2. As mentioned for the $ZZ \rightarrow \ell\ell\nu\nu$ analysis this channel is also divided into low and high pileup periods. In total there are 18 categories: three flavours ($e\nu e\nu$, $\mu\nu\mu\nu$, and $e\nu\mu\nu$); three jet multiplicities ($0j$, $1j$, and $2j$); and two data periods with low and high pileup. Details of this analysis on data can also be found in Ref [130].

- $H \rightarrow WW \rightarrow \ell\nu qq$:

Details of this analysis can be found in Ref [131]. Six categories are formed in this analysis. Jet binning, as it is done in the WW dilepton search to tag events from gluon fusion and VBF processes is done as well as separating by flavour of the charge lepton from the W decay. The limit setting for this analysis is performed using a similar method as in the $\gamma\gamma$ search; a fit-based search of a bump on the top of a large falling background in the reconstructed Higgs boson mass.

- $H \rightarrow ZZ \rightarrow \ell\ell qq$:

The high Higgs boson mass search with the $\ell\ell qq$ final state is performed by looking at

events with hadronically and leptonically reconstructed Z peaks. Further discrimination is obtained by separating the jets used to reconstruct the Z boson into light and heavy flavour components. Similarly to the $\ell\ell\nu\nu$ search, there are two regions in m_H with different cuts. This allows to profit out of the boost of the decay products. Details of this analysis can be found in Ref [132].

- $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$:

The search described in Section 5.1 is the actual analysis used in the combination.

5.2.2 Exclusion limits

The Frequentist statistical technique with the asymptotic approximation as mentioned in Section 5.1 and explained in Appendix A.3, is used to set the CL limits. On Fig. 5.9 it is shown the individual contributions for each of the channels included in the combination. The WW dilepton, the 4ℓ and the $ZZ \rightarrow \ell\ell\nu\nu$ channels by themselves can exclude a very large region of the searched phase space.

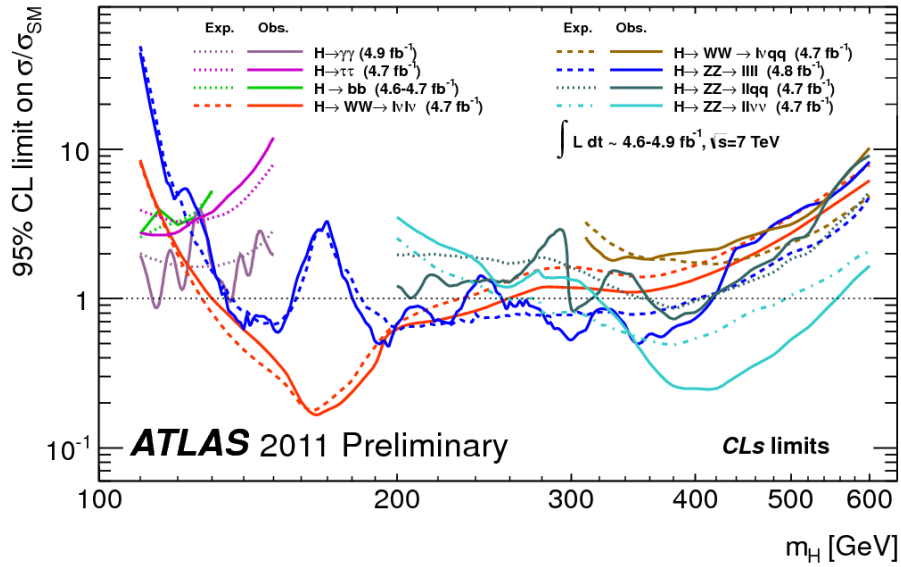


Figure 5.9: Observed and expected 95% CL cross-section upper limits for the individual search channels, normalised to the SM Higgs boson production cross-section, as a function of the Higgs boson mass. The expected limits are those for the background-only hypothesis i.e. in the absence of a Higgs boson signal [133].

The combination of the described SM Higgs boson analyses can be seen in Fig. 5.10. In the absence of a signal, the expected 95% CL exclusion region covers a range from 120 GeV to 555 GeV. The observed excluded region at 95% CL are from 110.0 GeV to 117.5 GeV, 118.5 GeV to 122.5 GeV, and from 129 GeV to 539 GeV. More important, the region between 130 GeV and 486 GeV can be excluded with a 99% CL. This can be seen in Fig. 5.11.

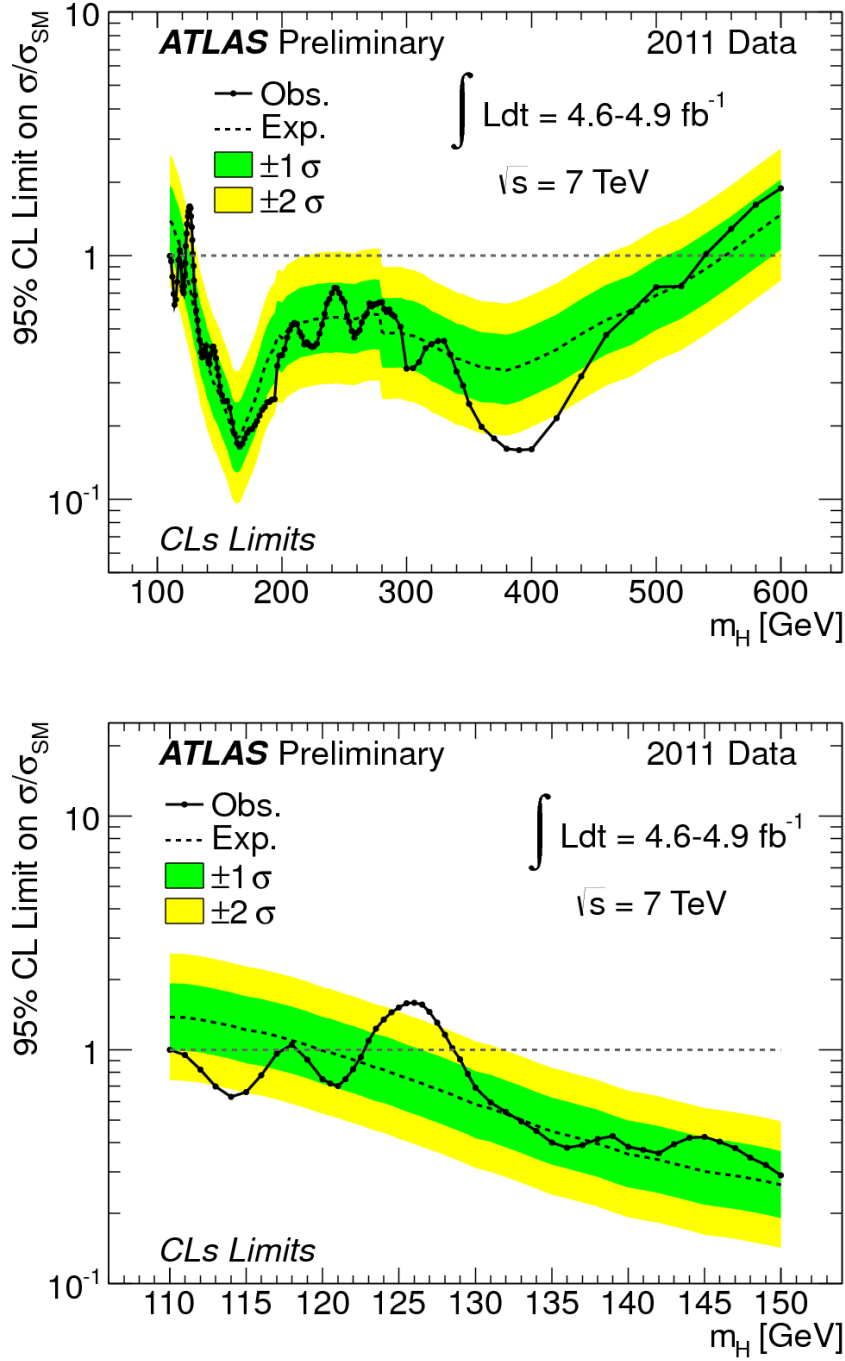


Figure 5.10: Observed and expected 95% CL combined upper limits on the SM Higgs boson production cross-section divided by the SM expectation as a function of m_H . The dotted curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals. Top: Full mass range considered in this analysis. Bottom: Zoom of the low mass region [133].

5.2. Statistical combination of Higgs boson searches in ATLAS

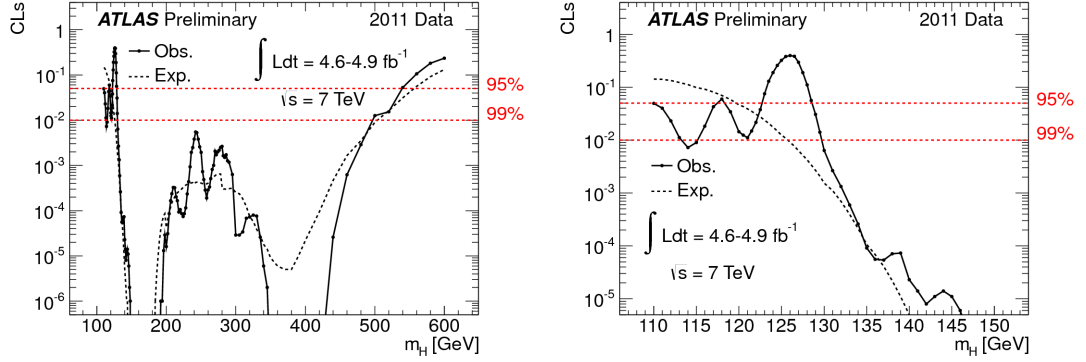


Figure 5.11: Value of the combined CLs for $\mu = 1$ (testing the SM Higgs boson hypothesis) as a function of m_H . Left: Full mass range considered in this analysis. Right: Zoom of the low mass region [133].

5.2.3 Compatibility with the background only hypothesis

An excess of events is observed at $m_H \sim 126 \text{ GeV}$. The significance of an excess is quantified by the p_0 probability that a background only experiment is more a signal-like than that observed. The p -value plots are shown in Fig. 5.12. The largest local significance for the combination is 2.6σ at 126 GeV. In the presence of a signal (dashed-line of Fig. 5.12), a significance of 2.9σ is expected.

The contributors to the observed excess are the high-resolution channels i.e. the $H \rightarrow \gamma\gamma$ and the $H \rightarrow 4\ell$, with individual significances of 2.8σ (1.4σ) and 2.1σ (1.4σ) observed (expected) respectively. This can be seen in Fig. 5.12 (Bottom).

Similar combined searches done by the CMS collaboration [134] have also seen an excess with a local significance of 3.1σ in the region close to $m_H=124 \text{ GeV}$. The combination of the ATLAS and CMS results would follow later this year. By summer 2012, the LHC should have produced about the same amount of data as the one delivered during 2011, with a the centre-of-mass energy of 8 TeV. This dataset will allow to clarify the nature of the observed excess of events, and independently confirm or disprove it.

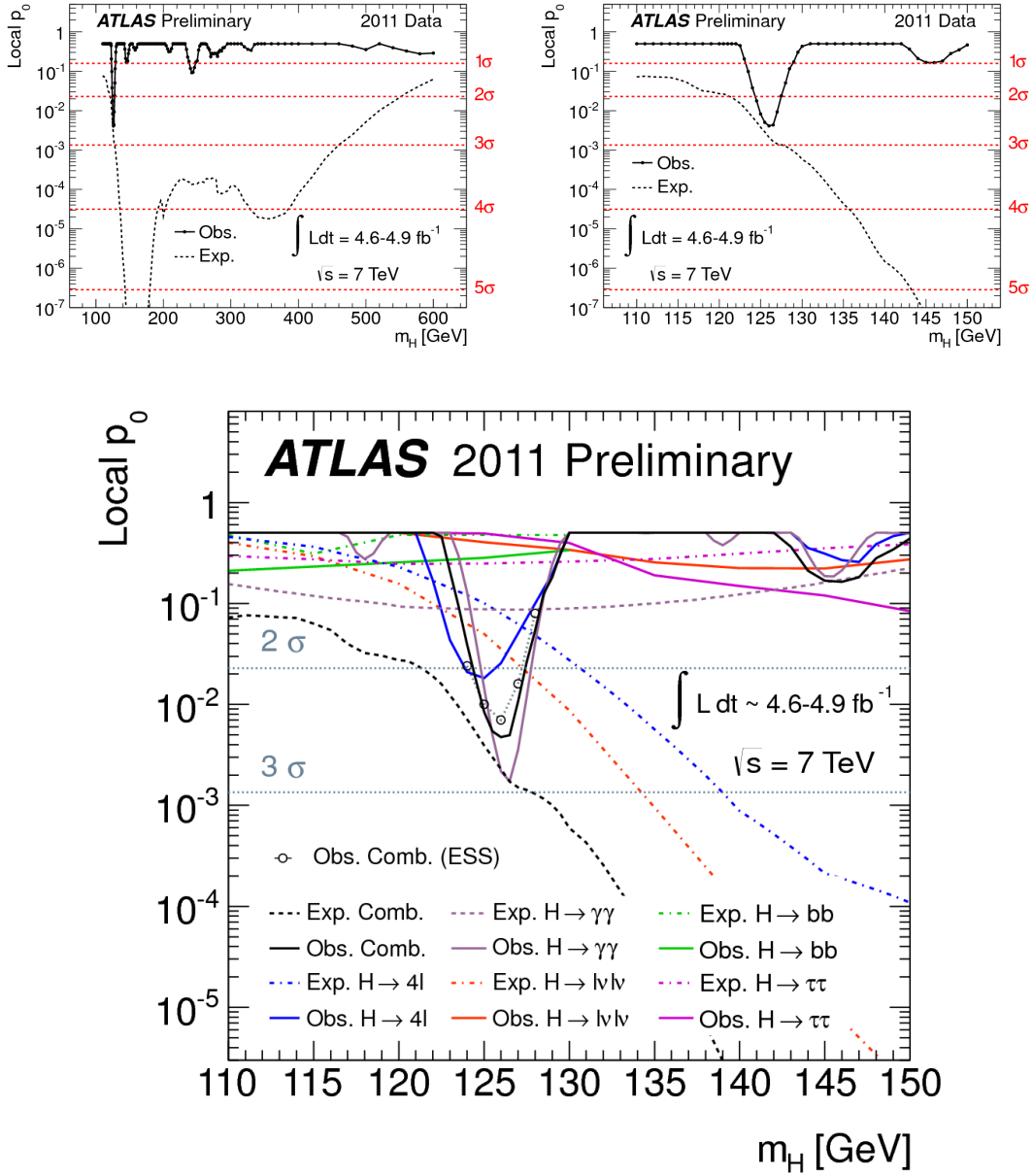


Figure 5.12: Local probability p_0 for a background-only experiment to be more signal-like than the observation. Top Left: Full mass range considered in this analysis. Top Right: Zoom of the low mass region. Bottom: Individual channels and the combination. The full curves give the observed individual and combined p_0 . The dashed curves show the median expected value under the hypothesis of a SM Higgs boson signal at that mass. The two horizontal dashed lines indicate the p_0 corresponding to significances of 2σ and 3σ . The points indicate the combined observed local p_0 estimated using ensemble tests (instead of the asymptotic approximation) and taking into account energy scale systematic uncertainties [133].

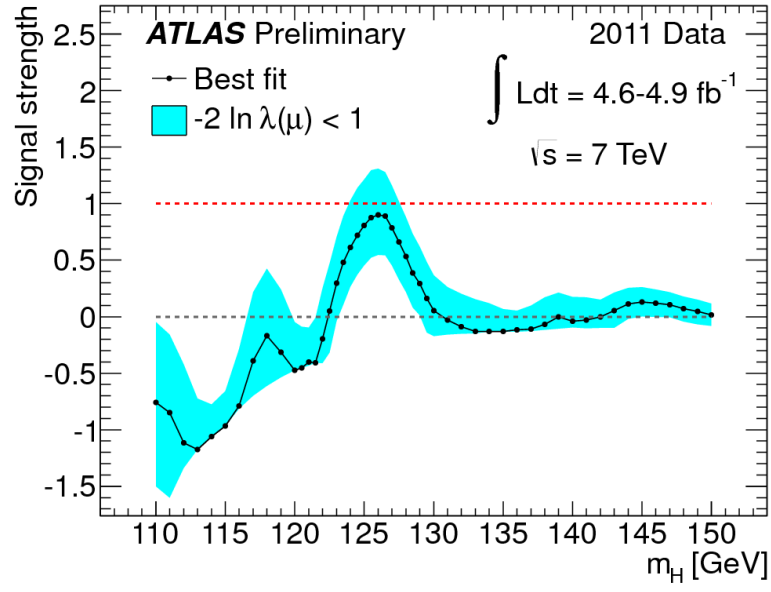


Figure 5.13: Best-fit signal strength $\mu = \sigma/\sigma_{SM}$ as a function of the Higgs boson mass hypothesis in the low mass range. The μ value indicates by what factor the SM Higgs boson cross-section would have to be scaled to best match the observed data [133].

6 Higgs boson Monte Carlo studies



“The mathematicians know a great deal about very little and the physicists very little about a great deal.”

Ulam Stanislaw.

The first section of this chapter revisits the sensitivity reach of the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ channel when the LHC tentative plans changed to use a $\sqrt{s}$ of 10 TeV instead of 14 TeV. The accelerator team considered that ramping the magnets to provide 10 TeV collisions could still be a threat for the health of the LHC. The prospects of the most sensitive of the Higgs boson searches in the medium mass region the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ was then updated. The second section of this chapter includes expectations considering scenarios where the LHC run at $\sqrt{s}$ of 10 and 7 TeV. Different assumptions of the level of understanding of the performance of the ATLAS detector were also considered.

The sensitivity reach for a given search translates into the amount of data (if finite) needed to either exclude it with a 95% confidence level, or claim a 5σ evidence, under certain predicted detector calibration and beam energy conditions.

The $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ analysis strategy is introduced, and a reevaluation of the already existing $\sqrt{s}=14$ TeV, to 10 TeV sensitivity studies is presented in Sec 6.1. The $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ analysis is described in detail. previous studies showed that a strategy by dividing this search in different jet bins would lead to larger discrimination of backgrounds. In the zero jet case, a full veto of events containing any reconstructed high P_T jet is applied. In the two jet case, events with the presence of two forward jets typical from the VBF topologies were selected. On previous studies the one jet case was somehow left aside since large theory uncertainties were thought to be a concern, and contamination of Top quark background into the searched regions was not completely under control. This was solved by developing a

Chapter 6. Higgs boson Monte Carlo studies

robust cut-based, number counting analysis, where dedicated control samples were built to normalise all sort of dominant backgrounds from data using little MC information, and where the various expected systematic uncertainties were carefully estimated.

6.1 $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$, sensitivity studies

The 4ℓ channel is also called the golden channel; it is the the cleanest of the Higgs boson final states with the Higgs boson decaying into a pair of Z bosons and each of these into a pair of opposite charged electrons or muons. The main production mechanisms for the four lepton channel at the LHC are the gluon-gluon fusion and the VBF production, Fig. 6.1 shows the LO Feynman diagrams for the Higgs boson production and its decay into 4ℓ .

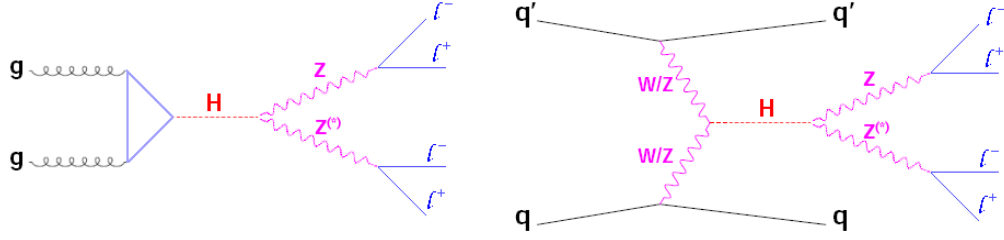


Figure 6.1: Feynman diagram for Higgs boson production through the gluon-gluon fusion and VBF production mechanisms, with the respective decay into four charged leptons.

This search has been extensively explored [27, 67], and was one of the stepping stones targeted in the design of the LHC and both the ATLAS and the CMS detectors. Back in 2008, it was necessary to update the sensitivity reach for a given luminosity, under the new LHC running conditions. This included the amount of luminosity needed to have a 95% CL exclusion. Using the existing 14 TeV MC simulations, and with the PDF reweight technique described in Chap. 4, it was possible to promptly re-estimate in an approximate manner the strength of the golden channel without regenerating the full set of MC events. Since the scope of this work was a rapid update, and given that the golden channel is well known to be robust and little affected by systematic uncertainties, the evaluations performed on this study assumed that the systematic uncertainties related to the background normalisations and object selections could be directly taken from already existing 14 TeV studies [27]. Therefore they could be neglected when compared to the very large statistical uncertainties expected with the luminosity target of $\int \mathcal{L} dt = 1 \text{ fb}^{-1}$.

6.1.1 Strategy

The branching ratio for $H \rightarrow ZZ$ is small, just about $\sim 4\%$ for a 130 GeV Higgs boson (see Fig.2.9). The final expected yields are even smaller since only $\sim 7\%$ of the neutral weak bosons decay into a pair of charged muons or electrons. For m_H below the ZZ threshold, one of the Z boson is an off-shell particle, its decay products are expected to have relatively small boosting. It is crucial to have as high reconstruction efficiency as possible, even for low p_T objects, this has to be in compromise with the identification quality, necessary to be able to discriminate SM backgrounds that could emulate a signal-like final state with four charged leptons.

The main background contributions are the irreducible production of SM diboson pairs ZZ , as well as two main reducible backgrounds that could emulate a final state with 4 leptons: Drell-Yan like events with the presence of two jets, and top pair production. The $Z + 2jets$ production, in particular the case where there are heavy flavour jets $Zb\bar{b}$, could potentially populate the signal region. With the Z boson decaying in a lepton pair, and the extra jets either faking electron-like electromagnetic showers or in the case of b -jets producing no isolated muons from semi-leptonic decays. In the case of $t\bar{t}$ events, each top quark could eventually decay in a W boson and a b , and then the weak boson could decay in a lepton neutrino pair; leading to two clean leptons from the W decays and two heavy flavour jets that could subsequently be misidentified as clean leptons coming from an off-shell Z boson decay.

Since the electron and muon reconstructions acceptances, efficiencies and systematic uncertainties are different, the 4ℓ search is typically divided on three independent subchannels: $4e$, 4μ and $2e2\mu$.

6.1.2 Object and Event Selections

The analysis was designed based on a robust rectangular cut-based approach. In order to maximise the background rejection and signal acceptance, the following event selections were applied:

- Four good charged leptons.
- Transverse momentum > 7 GeV
- Pseudorapidity in the range of $|\eta| < 2.5$
- At least two of the leptons should have a transverse momentum bigger than 20 GeV.
- Two pairs of leptons with same flavour and opposite charge.
- One of the pair of leptons should be compatible with an on-shell Z boson: satisfy $|m_{12} - m_Z| < 15$ GeV (12 GeV if $m_H < 180$)
- The invariant mass of the other lepton pair should satisfy $m_{34} > 20$ GeV (A tighter cut, function of m_H , is applied later in the selection.)
- Electrons are required to be isolated, with a ratio:

$$\sum \text{Track}_{P_T} / e_{P_T} < 0.15 \quad (6.1)$$

Tracks inside the cone formed by η and ϕ giving a $\Delta R < 0.2$ where $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

- Muons are required to be isolated, with a ratio:

$$\sum \text{Track}_{P_T} / \mu_{P_T} < 0.15 \quad \text{and} \quad \sum \text{Cluster}_{E_T} / \mu_{P_T} < 0.23 \quad (6.2)$$

Similarly to the electron case, tracks and cluster electromagnetic deposition inside the cone formed by η and ϕ giving a $\Delta R < 0.2$

- For electrons the impact parameter significance d_0/σ_{d_0} should be smaller than 6.0 while for muons it is required to be less than 3.5

For electron identification, information based on ID track pointing to the corresponding cluster and electromagnetic shower profiles, known as ATLAS “Loose” and “Medium” [27] electron identification [27, 114] (isEM) were used depending of the searched Higgs boson mass region.

For searches with $m_H < 180$ GeV, leptons were required to have a higher fake rejection due to the presence of irreducible backgrounds, therefore Medium electrons were needed. This requirement could be relaxed for $m_H \leq 180$ GeV to gain signal efficiency. Hence for masses larger than 180 GeV, Loose electrons were used. Some studies aimed to require a more dynamic number of Medium and Loose electrons, defining a 4ℓ specific smooth identification quality variable without compromising the background population in the signal region (see Fig. 6.2) were also done.

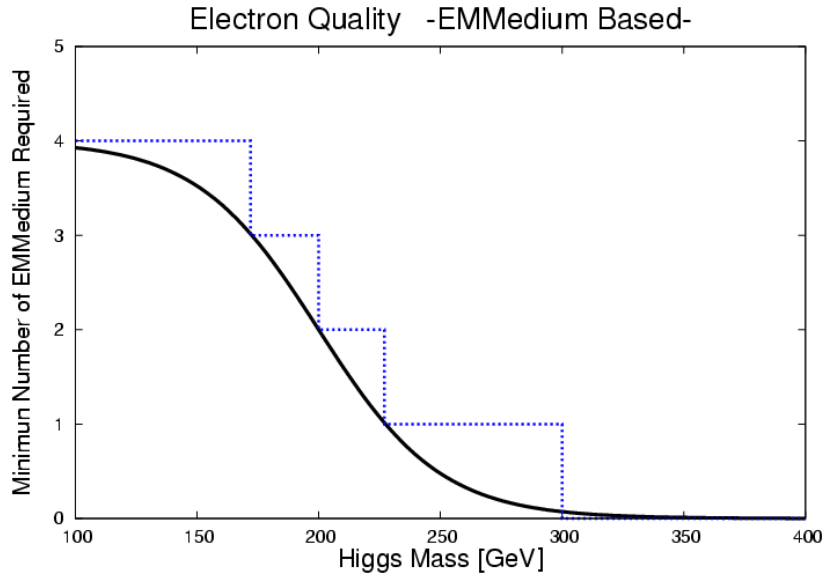


Figure 6.2: Study of minimum number of Medium-like electrons required in the 4ℓ searches aimed to define a 4ℓ specific smooth quality variable

The mass m_{12} is defined as the invariant mass of the lepton pair that better reconstructs an on-shell Z (the closest to m_Z). m_{34} is then defined as the invariant mass of the remaining lepton pair. Figure 6.3 shows the m_{12} and m_{34} distributions for a Higgs boson signal hypothesis of $m_H=200$ GeV. Similar distributions are seen for the irreducible ZZ background. For Higgs boson signals below the ZZ threshold, and for the irreducible backgrounds the m_{34}

tend to have a much softer contribution. Further details of the m_{12} and m_{34} distributions are given in Appendix A.5.

Since the m_{34} shape has a large dependency of $m_H (\lesssim 180 \text{ GeV})$, it was possible to gain further discrimination by applying a lower bound sliding cut, function of the tagged Higgs boson mass hypothesis. These cuts are listed in Table 6.1.

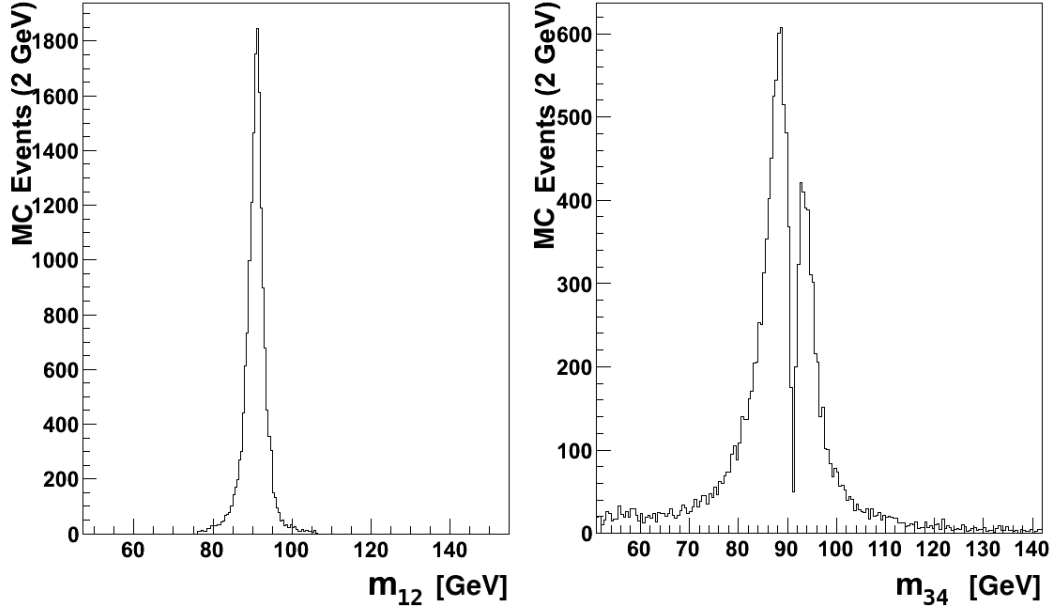


Figure 6.3: Shapes of m_{12} (Left) and m_{34} (Right) invariant masses for a $m_H = 200 \text{ GeV}$ Higgs boson signal.

Table 6.1: Lower bound on m_{34} as function of m_H hypothesis.

Mass [GeV]	120	130	140	165	180	200	≥ 300
Lower bound on m_{34} [GeV]	15	20	30	35	40	60	Same cut as m_{12} ¹

For searches above the ZZ threshold, both of the Z are expected to be on-shell; equal requirements of m_{12} and m_{34} are imposed. Since different cuts are applied for different search regions, the final discriminator $m_{4\ell}$ is expected to have slightly different shape for a given background. In Fig. 6.4 there are shown the shapes of the different signals and the irreducible ZZ background for this bins of the signal region.

The final discrimination was performed using windows on $m_{4\ell}$ keeping $\sim 95\%$ of the expected MC signal. Figure 6.5 shows the invariant mass signal and background shapes for a Higgs boson hypothesis of 130 GeV.

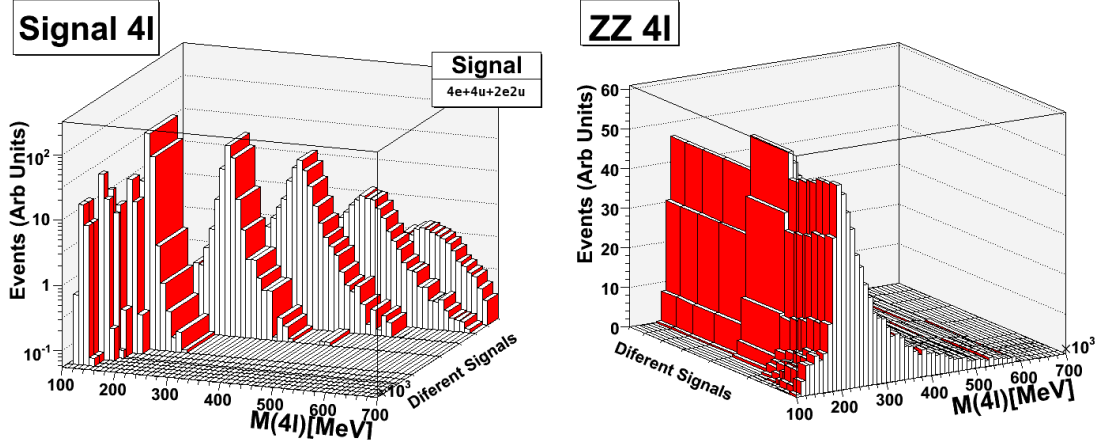


Figure 6.4: $m_{4\ell}$ shape for each of the m_H searched regions. Left: Higgs boson signals. Right: Irreducible ZZ background.

Table 6.2: Expected number of 4ℓ signal events with an integrated luminosity of 30 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ as function of m_H . The $4e$, 4μ and $2e2\mu$ channels are combined.

Mass [GeV]	120	130	150	165	180	200	400	500
Expected events	2.4	6.1	12.0	3.6	5.4	13.9	12.0	7.2

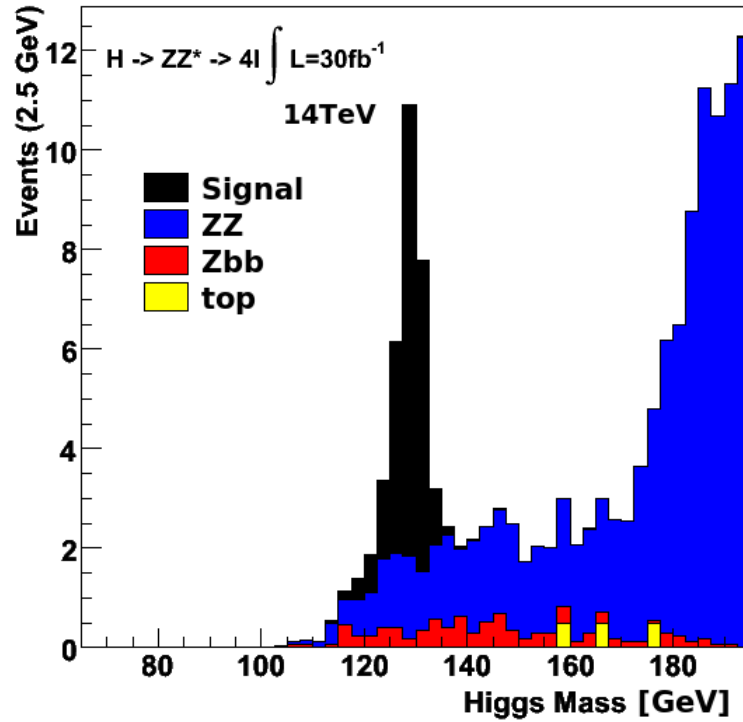


Figure 6.5: Expected number of 4ℓ events with an integrated luminosity of 30 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ for a Higgs boson mass hypothesis of $m_H = 130 \text{ GeV}$.

6.1.3 Statistical significance at $\sqrt{s} = 14$ TeV

The approximated statistical significance of the signal on the top of the expected addition of backgrounds was estimated based on the Poisson statistics. It is known to be more conservative and robust than the traditional $S = \frac{s}{\sqrt{b}}$, specially when the signal and background events are small. This number counting estimator is given by:

$$S = \sqrt{2[(s+b)\log(1 + \frac{s}{b}) - s]} \quad (6.3)$$

where s and b are the expected number of signal and background events in the $m_{4\ell}$ window. Figure 6.6 gives the expected significance of each of the 4ℓ subchannels as well as their combination assuming an integrated luminosity of $\int \mathcal{L} dt = 30 \text{ fb}^{-1}$ of $\sqrt{s} = 14$ TeV data. The individual contributions of each of the flavour subchannels was added in quadrature. The sensitivity of the sum of flavours is also compared with earlier results where a different MC simulations settings were used [27] and Gaussian significance was chosen.

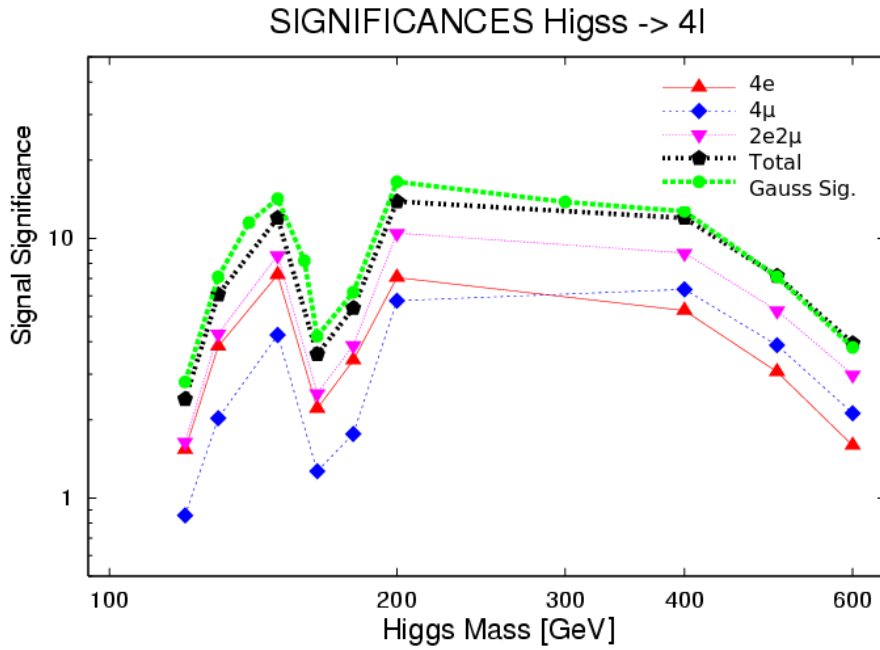


Figure 6.6: Expected signal significance with $\int \mathcal{L} dt = 30 \text{ fb}^{-1}$ of $\sqrt{s} = 14$ TeV data for the 4ℓ channel

With the 4ℓ by itself, an integrated luminosity of 30 fb^{-1} of 14 TeV data, could have provided sufficient statistical significance to discover a Higgs boson mass with 5σ evidence if m_H was in the region between 120-550 GeV, with a small exception around 165 GeV where only 3.5 sigma could have been possible.

6.1.4 10 TeV results using PDF reweight

The MC samples were initially simulated at $\sqrt{s}=14$ TeV only. At the time this study was presented 10 TeV results were needed, but only a handful of signal samples with small MC statistics were re-simulated. The formalism described in Sec. 4.2 to re-weight the background MC samples based on event-by-event PDF ratios was applied. Further details, as well as the validation of the PDF reweighting procedure are given in Appendix A.2.

Since some signal samples were already re-simulated at 10 TeV, it was possible to obtain two sets of 10 TeV results. Reweighting both signal and backgrounds samples; or reweighting only the backgrounds simulations and using the 10 TeV Higgs boson signals. The compatibility of these results also contributed to the validation of the scaling procedure.

In Fig. 6.7 (Left) it is shown the expected statistical significance of the Higgs boson signal on the top of the backgrounds assuming $\int \mathcal{L} dt = 1 \text{ fb}^{-1}$ of $\sqrt{s}=10$ TeV data.² On Fig. 6.7 (Right), it is shown the 80% CL excluded SM Higgs boson cross-section times the $H \rightarrow ZZ \rightarrow 4\ell$ branching ratio for two integrated luminosity scenarios, 100 and 500 pb^{-1} .

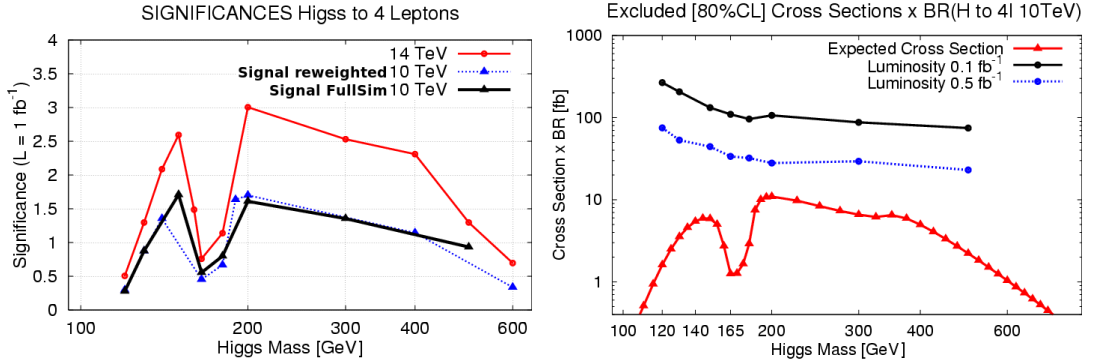


Figure 6.7: Left: Comparison of sensitivity in the 4ℓ channel between 14 TeV (red), and 10 TeV (black and blue). In the blue plot the PDF re-weight method was applied to both signals and backgrounds, while in the black curve only the backgrounds are weighted because the signal was already simulated at 10 TeV. Right: Upper cross-section that the 4ℓ channel alone would exclude at 95% of CL with two different luminosities, compared with the SM cross-sections.

With the LHC running at 10 TeV and $\int \mathcal{L} dt = 0.5 \text{ fb}^{-1}$ of integrated luminosity, the golden channel could have claimed and exclusion of a Higgs boson with 20 times the production cross-section predicted by the standard model.

For this search the loss of sensitivity due to a smaller $\sqrt{s}$, could only be recovered if more

²It is worth mentioning that the connecting lines among the different m_H do not necessarily reflect the expected behaviour of the interpolated points. Their connection was simply based on the existing signal samples, which unfortunately did not correspond to a common set of values. The most evident case is at $m_H=150$ GeV, where the signal sample that was possible to reweight to 10 TeV did not exist. It created an artificial loss of significance when interpolating between 140 and 165 GeV.

luminosity was delivered. On Fig. 6.8 (Left), it is shown the required amount of integrated luminosity to be able to exclude a SM Higgs boson at certain CL. As the branching fraction, and signal to background ratio are best for m_H close to 200 GeV, the point at this Higgs boson mass hypothesis could be excluded at 95% CL with as little as $\int \mathcal{L} dt = 2 \text{ fb}^{-1}$. Higgs boson masses close to 500 GeV or 130 GeV, would have required an integrated luminosity of ~ 6 and $\sim 8.5 \text{ fb}^{-1}$ respectively. The m_H points at 110 and 600 GeV have a very small $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ expected number of events, they would require luminosities of several tens of inverse femtobarns.

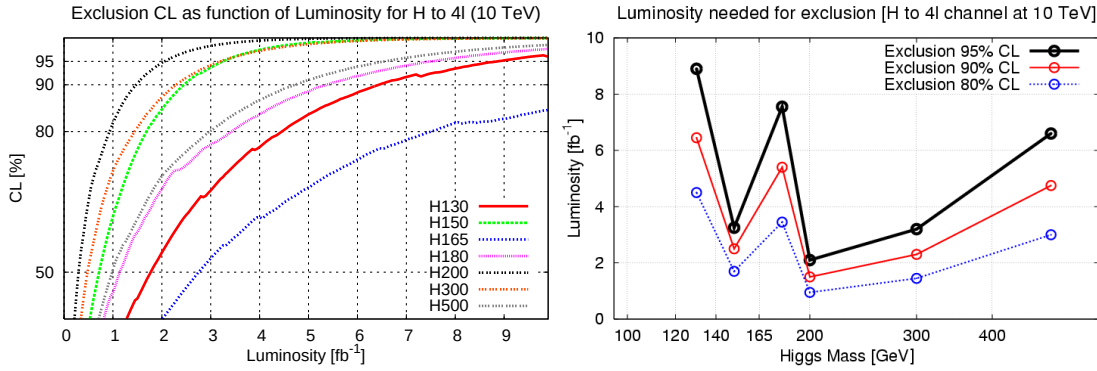


Figure 6.8: Required luminosity to exclude a Higgs boson in the 4ℓ channel with 10 TeV data. Left: excluded confidence level for a given luminosity for various Higgs boson mass signals. Right: Luminosity required to exclude a Higgs boson at 80, 90 and 95% CL as function of m_H .

This set of results for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ channel, confirmed that the SM Higgs boson searches were still plausible even with the LHC beams at a portion of its nominal energy. Clearly the amount of integrated luminosity was restated to be a key issue for Higgs boson sensitivity. With the appropriate amount of luminosity (between a factor of 2 and 3 depending of m_H) one could partially heal the sensitivity lost given by the reduction of the energy collisions.

This conclusions certainly does not apply to other searches performed at the LHC. The rapidly growing dependencies of the mass and production cross-section of hypothetical SUSY particles with respect to the $\sqrt{s}$ restricts this statement to SM Higgs boson searches.

6.1.5 Fit based approach

The final state of 4 isolated electrons and muons coming from a common vertex close to the interaction point allows a very efficient rejection of reducible backgrounds (Zbb and Top), leaving the direct production of ZZ as main component.

Specific control regions to measure the irreducible backgrounds directly from data were also studied. One can profit out from the presence of heavy flavour jets to build a sample populated with two clean leptons and a heavy tagged jet, or with lepton-like objects where the impact parameter is large, compatible with the longer b decays. For the top pair production, one could also explore the regions on the sidebands of the leptonically reconstructed Z boson; or tag events with large missing transverse energy. This is possible thanks to the origin of the leptons in $t\bar{t}$ events: ($W \rightarrow \ell\nu$).

For the dominant irreducible background, it can be statistically separated by doing a parametrisation and using fit based formalisms [27]. This has several advantages, the most important is the possibility of constraining the ZZ background normalisation directly from data. This is not possible when taking the number counting approach in $m_{4\ell}$ windows.

The models used to describe the Higgs boson signal and the ZZ background along the full $m_{4\ell}$ spectra was given by:

- For signal: CrystallBall

$$f(m_{\text{signal}}) = \frac{\left(\frac{n}{|a|}\right)^n e^{-1/2a^2}}{\left(\frac{n}{|a|} - |a| - x\right)^n} \Big|_{x < -|a|}, e^{\left(-\frac{1}{2}\left(\frac{x-m}{sx}\right)^2\right)} \Big|_{x > -|a|}$$

- For the $ZZ^{(*)}$ background: Composition of fermi distributions

$$f(m_{ZZ}) = \frac{p0}{\left(1 + e^{\frac{p6-m_{ZZ}}{P7}}\right)\left(1 + e^{\frac{m_{ZZ}-P8}{P9}}\right)} + \frac{p1}{\left(1 + e^{\frac{p2-m_{ZZ}}{P3}}\right)\left(1 + e^{\frac{p4-m_{ZZ}}{P5}}\right)}$$

The relatively large number of parameters (nine) for the background description, are needed if a common model is to be used for low and high Higgs boson mass searches. Figure 6.9, shows the template models fitted on the top of generated toy pseudoexperiments created from the shapes obtained by the fully simulated MC samples. The generated toys, are shown for background only and signal plus background hypotheses with a Higgs boson mass assumption at 130 GeV. The integrated luminosity corresponds to

With a large number of pseudoexperiments it is possible to build a Likelihood test statistics to probe a background only hypothesis, on background only, and on signal plus background templates. This profiled log-likelihood ratio (LLR) Frequentist formalism is further described in Appendix A.3.

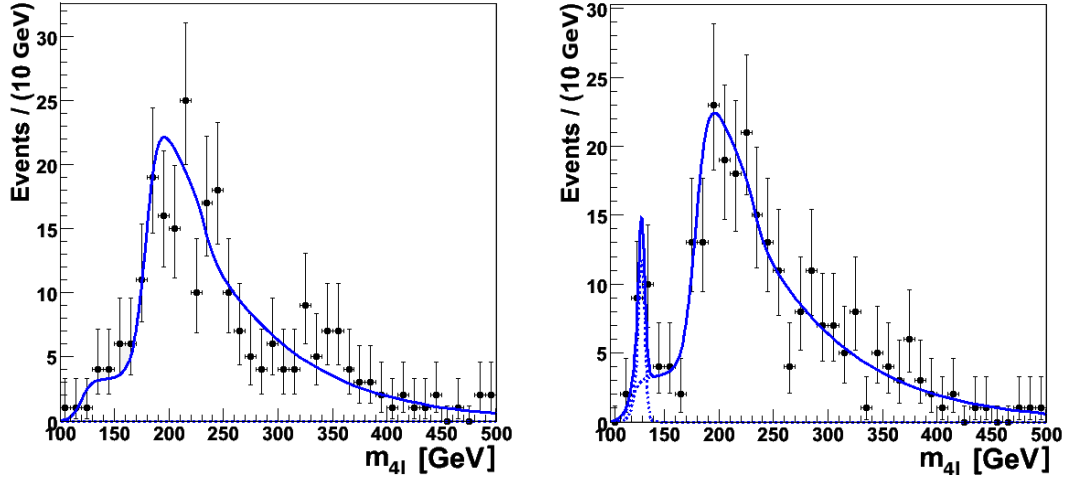


Figure 6.9: Shapes of the fitted models. Left and Right plots show an example of a toy pseudoexperiment and its best fits, for background only and signal plus background templates respectively.

The extracted significances using the fit based technique are shown in Fig. 6.10; they are also compared to the more aggressive number counting approach where windows on $m_{4\ell}$ are used. An integrated luminosity of 1 fb^{-1} and $\sqrt{s} = 10 \text{ TeV}$ (PDF reweighted) are assumed.

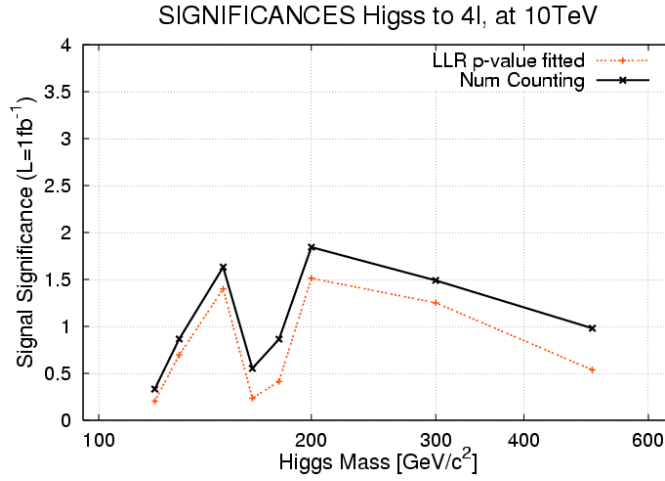


Figure 6.10: Comparison of sensitivity values obtained with number counting and using the fit-based likelihood formalism.

6.2 $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, design of analysis strategy

It has been known for some time that the most sensitive Higgs boson search channel in the early LHC data was going to be the, $H \rightarrow W W \rightarrow \ell \nu \ell \nu$ channel. However, initial expectations of first few hundred pb^{-1} of data were known to consist of collisions at $\sqrt{s} = 10$ TeV or less, rather than 14 TeV; it was therefore necessary to re-evaluate the physics potential at this lower centre-of-mass energy. The present chapter documents a study of this issue, including a detailed cut optimisation, control samples, and the associated systematic errors for an aggressive and a conservative scenario.

The chapter documents a study of this channel at a centre-of-mass energy of 10 TeV, with projections for 7 TeV estimated using a reweighting technique.

Section 6.2.2 describes the cuts used to preselect signal events and the cross-sections of signal and background processes remaining after the selection cuts. Then three separate Sec. 6.2.5, 6.2.6 and 6.2.7, describe the specific cuts, control samples used to estimate the normalisations of the various background contributions and results for each of the exclusive jet bins this search is divided on. Finally Sec. 6.2.8 presents the statistical combination of the individual jet-binned searches with an estimate of the impact of running at a centre-of mass energy of 7 TeV using 10 TeV MC re-weighted event-by-event at the parton level.

The different signal and background processes considered for this search were simulated at a $\sqrt{s} = 10$ TeV using full simulation of the ATLAS detector. The backgrounds considered include the continuum $W W$ (with corrections from $g g \rightarrow W W$), top production, W and Z production, multijets, as well as other processes including $V + \gamma$ and diboson production of $Z Z$ and $W Z$. Details of this and both gluon initiated and VBF Higgs boson signals are given in Chap. 4.

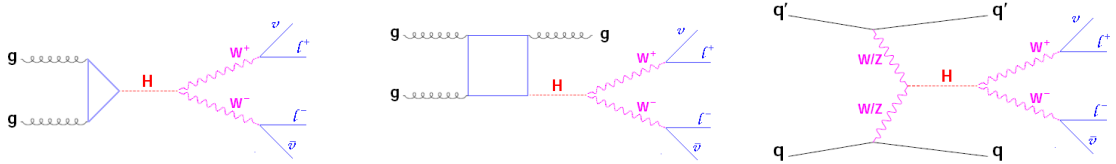


Figure 6.11: Feynman diagrams for gluon fusion and VBF Higgs boson production and their decay into a charged weak boson pair. Both of the W bosons decay leptonically.

6.2.1 Strategy

Because of the presence of two neutrinos in the final state, no narrow mass peak can be reconstructed in this channel. The analysis is therefore a counting experiment. Fit-based methods have been studied in the context of 14 TeV running in the past, but the present work is modelled more closely on Ref [27, 102] since the pure counting methods in the latter study are less complex and therefore more suitable for a first upper bound on the Higgs boson

production cross-section with the early data.

Moreover, because the backgrounds are at least as large as the signal, systematic errors play a crucial role. The presented work, like many of the studies that have come before it, features a strong emphasis on control samples that can be used to check the normalisation of the various backgrounds in data and the systematic errors associated with each of these auxiliary measurements. This study introduces several new control samples to estimate non-dominant backgrounds which were either neglected or taken from MC in previous studies. One of them, the W +jets control region, is used directly in the computation of the final limit. The other two, which normalise the $b\bar{b}$ and Z +jets backgrounds, are presented only as checks on the normalisation, since the contribution from these backgrounds is expected to be negligibly small after cuts.

The basic set of kinematic cuts are optimised with these control samples and uncertainties in mind, and results are presented for two alternative sets of cuts motivated by different assumptions about the detector performance. These two sets of cuts are referred to as the “Aggressive” and “Conservative” scenarios³:

- The “Aggressive” scenario consists of cuts optimised for use with a nominal detector performance scenario. In particular, this scenario assumes that jets can be accurately reconstructed down to the level of 20 GeV, and that a missing transverse momentum cut of 30-40 GeV is sufficient to suppress backgrounds like Z +jets and $b\bar{b}$ to negligible levels.
- The “Conservative” scenario is intended to be more robust in the case of the very early data, where some aspects of detector performance may not yet have reached their nominal performance. This scenario assumes that jets can only be reconstructed reliably if their P_T is larger than 30 GeV (40 GeV for jets with $|\eta| > 3.2$) and that a cut on the missing P_T of 50 GeV is required in order to suppress backgrounds from $Z \rightarrow \ell\ell$ and $b\bar{b}$. Since measures like these are not expected to be necessary except in the very early data, and since the effective cross-section after cuts for $H \rightarrow WW + 2j$ is quite small, the combination in the “conservative” scenario does not include the $H \rightarrow WW + 2j$ channel.

6.2.2 Objects and Event Selection

The event selection can be separated on three categories: the **preselection**, requires the presence of clean objects (electrons, muons and jets) and applies cuts common for the searches on the independent jet categories; the **specific jet cuts**, enhance signal events with zero, one

³The names “conservative” and “aggressive” are based on the expected sensitivity for the combined search using all jet multiplicities; if one considers the $H + 0j$ channel alone, the sensitivity is higher in the “conservative” scenario than in the “aggressive” one because the increase in signal efficiency one obtains by relaxing the jet veto (rejection of events with the presence of a high P_T jet) outweighs the increase in top background, which is already small in this analysis. In $H + 1j$ and $H + 2j$, the top background plays a larger role.

or two jets; and the final **topological cuts**, which are designed to separate the irreducible WW continuum.

The baseline preselection cuts to select signal events are described below:

- **Trigger**

In contrast to the studies presented in [27], only single lepton triggers with transverse momentum larger than 10 GeV (*e10_medium* and *mu10*) are used; the double-lepton triggers are ignored in the present study. Relying solely on single-lepton triggers lowers the total trigger efficiency slightly; this approach is intended to lessen the burden associated with understanding the efficiency of a trigger selection consisting of a logical “or” of several distinct menus in the early data.

- **Selection of Objects**

Events must have two isolated leptons with $P_T > 15$ GeV:

- Muons are reconstructed using the STACO algorithm. They are required to be “combined” muons; that is, there should be an associated track in the inner detector. The χ^2 of the match between the inner detector track and the track in the muon spectrometer is required to be smaller than 100. The muon candidates must lie in the pseudorapidity range with $|\eta| < 2.5$ and the impact parameter significance with respect to primary vertex must be smaller than 10.
- Electrons are selected using the standard ATLAS “tight” electron identification. Their pseudorapidity as measured by cluster information is required to be within $|\eta| < 2.47$ and outside the crack region, $1.37 < |\eta| < 1.52$. Additionally, the impact parameter significance with respect to the primary vertex must be < 10 .
- Normalised calorimeter isolations is required $\sum \text{Cluster}_{E_T} / P_T < 0.1$, and normalised track isolation $\sum \text{Track}_{P_T} / P_T < 0.2$ in cones of $\Delta R < 0.3$.
- Lepton candidates are required to be separated by $\Delta R > 0.3$ for technical reasons related to the isolation cuts; in the calorimeter isolation variable, the subtraction of the energy deposition left by an additional identified lepton is non trivial.

The justification for these cuts, along with the performance in terms of lepton efficiency and fake rejection, is discussed in Appendix A.7.1.

- In order to suppress backgrounds with three or more leptons, a third lepton veto is implemented; events with a third lepton (including electrons which only pass the “Medium” electron selection as well as electrons in the crack region) are rejected.
- The dilepton invariant mass, $m_{\ell\ell}$, must be larger than 15 GeV
- As described earlier, In the aggressive scenario, the missing transverse momentum is required to be large, $P_T^{\text{miss}} > 30$ GeV for the different flavor channels. Since the Z -jets background has a large cross-section and a steeply falling P_T^{miss} distribution, this

cut is tightened to $P_T^{\text{miss}} > 40$ GeV for same flavor channels to ensure that the Z background is small enough after cuts. In the conservative scenario a cut of 50 GeV on both cases is applied.

- $m_T(\ell\ell\nu) > 30$ GeV where $m_T(\ell\ell\nu) = \sqrt{2 \cdot P_T(\ell\ell) \cdot P_T^{\text{miss}} \cdot [1 - \cos(\Delta\phi(\ell\ell))]}$

After the jet selections are applied, the topological cuts that include:

- Rejection $Z \rightarrow \tau\tau$ decays.⁴
- The dilepton invariant mass, $m_{\ell\ell}$, must smaller than 50 GeV.
- To exploit differences in the helicities of the W bosons in signal and background, the dilepton opening angle in the transverse plane, $\Delta\phi(\ell\ell)$, is required to be less than 1.3 radians.
- The mass of the transverse system is required to be less than the Higgs boson mass hypothesis:

$$m_T < m_H, \quad m_T \equiv \sqrt{(E_T^{\ell\ell} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}})^2} \quad (6.4)$$

where $E_T^{\ell\ell} = \sqrt{(P_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$ and $E_T^{\nu\nu} = |P_T^{\text{miss}}|$

6.2.3 Control Samples

The cuts described in the previous subsection define a region of phase space referred to in this document as the “Signal Region”. Because of the lack of a clear mass peak, it is not possible to normalise the background in the Signal region by interpolating between two sidebands as can be done, for example, in $H \rightarrow \gamma\gamma$ or the 4ℓ searches described earlier.

Instead, the control regions used here are only on one side of the signal region in any given discriminating variable, and systematic errors in the predicted ratio of background normalisations in the signal region and control region take on a larger role in the analysis.

Ideally one wants to construct a clean control region for each of the important backgrounds (i.e. no contributions from other processes in the controls samples), but often subtraction of some other contributions is needed in order to get a non-biased estimation of the normalisation. From MC, one can estimate the ratios of the effective cross-sections for a given background process, XX , in the signal region and in the corresponding control region; this ratio is defined as α^{XX} , and among control regions as well, defined as β^{XX} ratios.

⁴The visible energy fractions, x_τ^1 and x_τ^2 for the two leptons are reconstructed in the collinear approximation, and if both are positive and $|m_{\tau\tau} - m_Z| < 25$ GeV, the event is discarded. The $Z \rightarrow \tau\tau$ process is really only a background for the control region discussed in Sec. 6.2.5 because it tends to be back-to-back, but the $Z \rightarrow \tau\tau$ rejection cut is applied in the signal region as well for the sake of consistency.

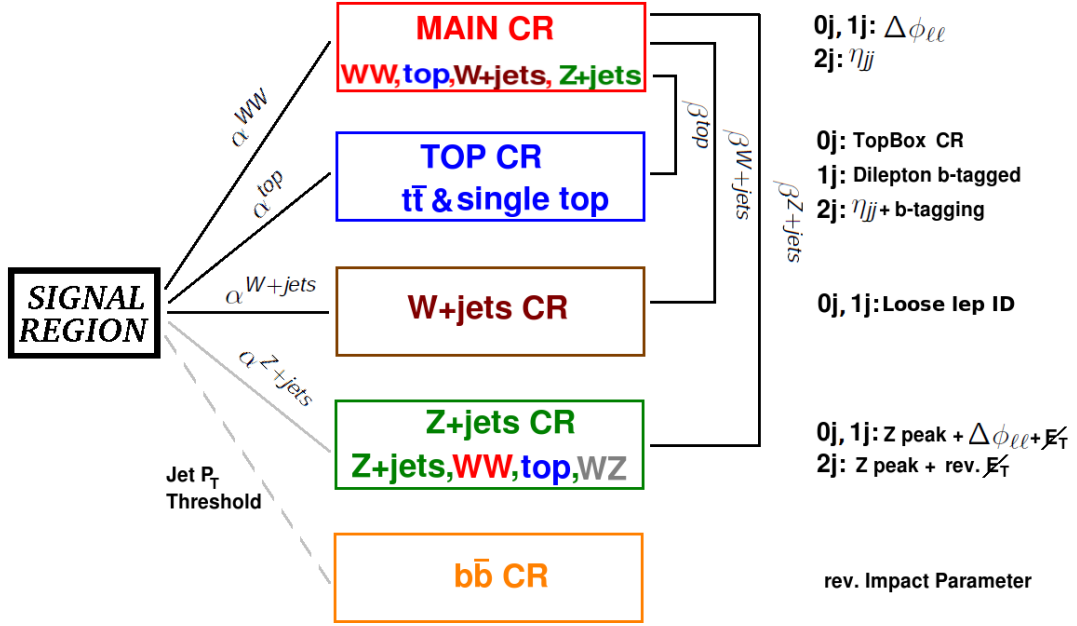


Figure 6.12: Schematic description of different background control regions and the methods that were applied in the present analysis. The information of the right illustrates the main discriminating criteria used to separate each process from the signal region.

The expected contribution of a certain background XX into the signal region would be:

$$N_{XX}^{SR} = (M_{data}^{CR_{XX}} - N_{YY}^{CR_{XX}}) \alpha^{XX} \quad (6.5)$$

here the contamination of the background process YY , is subtracted from the measurement in the control region $M_{data}^{CR_{XX}}$ to adequately estimate XX . $N_{YY}^{CR_{XX}}$ could be taken from a MC simulation prediction, but if there are reasons such as large associated systematic uncertainties, YY could also be extracted from the control region which is already used to estimate YY in the signal region, N_{YY}^{SR} . This procedure is done for processes that are not easy to disjoint, in particular the WW analyses need to deal with contamination of top and W +jets (or Z +jets in the VBF case) in the control region built to measure the WW background.

$$\begin{aligned} N_{WW}^{SR} &= (M_{data}^{CR_{Main}} - N_{Top}^{CR_{Main}} - N_{W+j}^{CR_{Main}}) \alpha^{WW} \\ &= (M_{data}^{CR_{Main}} - M_{data}^{CR_{Top}} \beta^{Top} - M_{data}^{CR_{W+j}} \beta^{W+j}) \alpha^{WW} \end{aligned} \quad (6.6)$$

The detailed discussion of the control sample strategy in this analysis is therefore divided into several subsections, each describing the cuts and systematic errors for one of the control samples. Figure 6.12 shows a schematic overview of the various control samples and how backgrounds in the different regions are normalised.

- In the zero jet channel the dominant background contribution is from continuum WW production. It is normalised using a sample of events with reversed cuts on $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$. It is represented in Fig. 6.12 as the red box labelled “Main CR”. This region is populated primarily by continuum WW events, but there is also non-negligible contamination from top, W +jets, and Z +jets. In the zero and one jet cases the contributions from top and W +jets are normalised using the control samples described below; while in the VBF channel it is done for top and Z +jets. The Z +jets contribution to this region in the zero and one jet channels is taken from MC, although a control sample that could be used to normalise it is discussed below.
- Backgrounds from top quark production are dominant in the one and two jets searches. The top background in both the signal region and the WW control region are normalised using a set of cuts designed to select top pair events. In the zero jet case events where one of the W bosons from the top quarks decays leptonically and the other decays hadronically are selected. In the one and two jet analysis a region populated with b -tagged jet(s) is used to normalise the top background. Additionally in the two jet case, the pseudorapidity gap between the tagged jets required on the Signal Region is reversed. These regions are represented in Fig. 6.12 as the blue box labelled “Top CR”. There is a non-negligible contamination from W +jets events in the Top control region for the zero jet channel. In the final results, the W +jets contribution is taken from MC, but studies to designed methods to estimate its contribution by varying the jet veto P_T threshold have been performed.
- The W +jets background, where one jet produces a fake lepton, contributes to both the signal region and the WW control region. The control sample which normalises this background is represented by the brown box labelled “ W +jets CR” in Fig. 6.12, is based on a loosened electron definition and is intended to control the normalisation of events where a jet is misidentified as an electron. In the present study, there is no dedicated control sample to normalise the contribution from events where the W is accompanied by a non-isolated muon from a heavy flavour decay. For now, the normalisation of this contribution is taken from the loose-electron control sample with the help of a scale factor derived from MC. In principle, one would expect that a control sample with loosened isolation and impact parameter cuts would be a suitable tool to normalise the W +jet contribution.
- The normalisation of the Z +jets background can be checked by varying the cut on p_T^{miss} and looking at events with $m_{\ell\ell}$ close to m_Z . This control region is represented in Fig. 6.12 by the green box labelled “ Z +jets CR”. The Z +jets background that is used in the limit-setting calculation is taken from MC because the in-situ estimate of the Z background is not expected to alter the results in a significant way.
- Similarly, the normalisation of the $b\bar{b}$ background can be checked by reversing the impact parameter cuts and loosening the isolation and jet veto cuts. This control sample is not used to normalise the W +jets background in the top box control sample

because the top box control sample consists of events with only one lepton. discusses this possibility in detail. However, since the MC prediction of the $b\bar{b}$ cross-section is negligibly small, this control sample is not used in the final limit calculation. The $b\bar{b}$ control region is represented in Fig. 6.12 by the yellow box labelled “ $b\bar{b}$ CR”.

Each of these control regions is sensitive to the normalisation of one of the backgrounds. In order to turn the measurement of the event rate in a given control region into an estimate of the normalisation of the corresponding background in the signal region, it is necessary to multiply by a constant, taken from MC.

These “extrapolation coefficients” are denoted as α^{XX} , where XX can be WW , Top, or W +jets, depending on the control sample in question. In Fig. 6.12, each of these is represented by a solid line connecting one of the control region boxes to the signal region box. The dashed line indicates similar background normalisation measurements that could be performed for the minor backgrounds, from Z +jets (in the zero and one jet case) and $b\bar{b}$ but are not actually used in the limit-setting calculations of this search.

6.2.4 Statistical techniques

The sideband measurements described in the previous subsection can be used in data to determine the normalisations for the most important backgrounds in the signal region. Once this is done, it is still necessary to turn the results into a concrete statement about nature; to make this statement more robust, it is desirable to study multiple statistical methods.

Toy MC outcomes are generated, consisting of the number of events observed in the signal region and in the control regions described in the above subsections. A sample of outcomes is generated with no signal included, and samples are generated with signals corresponding to the various Higgs boson masses are generated as well. For each outcome, an upper limit on the Higgs boson cross-section is computed, and the discovery estimator (Likelihood Ratio) is evaluated. Given the full sets of outcomes, p -values are computed for both techniques by computing the fraction of background-only outcomes for which the estimator is larger than the median of the distribution for signal-plus-background outcomes. The significance Z is expressed in terms of the p -value using the formula

$$Z = \sqrt{2} \operatorname{erfc}^{-1}(2p) \quad (6.7)$$

The figure of merit for limits is the fraction of outcomes in which a signal is excluded when that signal is in fact present; this is straightforward to compute given the toy MC samples. A 95% confidence level limit is considered; this means that for an ideal upper limit, the probability that the signal hypothesis is excluded in a signal plus background outcome should be 5%.

Appendix A.3 gives some specific details of this procedure.

6.2.5 0 jet

Events without hard jet activity are selected. This intends to reject events with top-like backgrounds as well as events with non-genuine missing transverse energy. Figure 6.13 shows the LO Feynman diagram for gluon gluon fusion Higgs boson production mechanism.

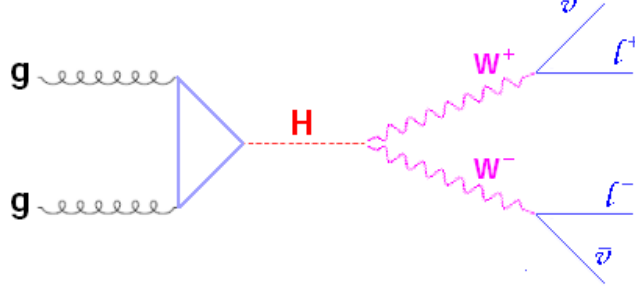


Figure 6.13: Feynman diagram for gluon fusion Higgs boson production and its decay into a charged weak boson pair, where both of the W bosons decay leptonically.

Events in the zero jet category are selected based on the following criteria:

- Events are rejected if they contain any hard jets. Based on the scenario considered, jet selections are required to have $P_T > 20$ GeV and $|\eta| < 4.8$ in the aggressive analysis, or $P_T > 30$ GeV and $P_T > 40$ GeV for $|\eta|$ smaller or larger than 3.2. Jets are reconstructed from topological clusters using a cone algorithm with a radius of 0.4.
- The transverse momentum of the dilepton system must be larger than 30 GeV.

Table 6.3 shows the cutflow for the $e\mu$ channel for a representative Higgs boson mass of 170 GeV in the aggressive scenario; cutflow tables for ee and $\mu\mu$ channels as well as cutflow tables for the conservative scenario and mass scan tables for all scenarios are shown in Appendix A.7.5.

Control Samples and Systematics for $H \rightarrow WW + 0j$

Table 6.4 shows the cross-sections for signal and background in each of the control regions used to normalise the different backgrounds in the zero jet search.

As mentioned above, the WW control sample is not a pure sample of continuum WW events, so some of the other control samples (for example the top box) are used to normalise contributions to the WW control sample as well as the signal region. The procedure to convert the measurement in one of the other control samples to an estimate of the contamination in the WW control region also involves an extrapolation coefficient taken from MC, but to distinguish these extrapolation coefficients from the ones for the signal region, they are denoted as β^{XX} . These extrapolations are represented in Fig. 6.12 by a solid line connecting two

6.2. $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, design of analysis strategy

Table 6.3: Cross-sections (in fb) for the $e\mu$ channel, for representative Higgs boson mass 170 GeV in the aggressive scenario. The last four columns are the backgrounds considered. Contributions from other backgrounds like $W\gamma$, WZ and ZZ are evaluated to be small and therefore are not listed. Since no MC events pass the full selections for W +jets, the expectation here is listed as zero, but as the other backgrounds it is explicitly normalised based on a data-driven technique.

Cut	$gg \rightarrow H$	VBF	WW	$t\bar{t} + Wt$	W +jets	Z +jets
2 Leptons	83.3	12.3	568	3870	66.2	1930
$m_{\ell\ell} > 15$ GeV	80.3	11.9	561	3840	55.6	1930
$p_T^{\text{miss}} > 30$ GeV	72.2	10.5	396	3270	31.8	137
$m_T^{\ell\ell\nu} > 30$ GeV	71.1	9.96	375	2840	31.8	54.4
Jet Veto	32.9	0.273	207	23.2	23.1	23.7
b -jet veto	32.8	0.27	206	20.5	23.1	23.7
$p_T^{\ell\ell} > 30$ GeV	31.7	0.258	184	19	16.8	5.17
$Z \rightarrow \tau\tau$ rejection	31.6	0.258	180	18.3	16.8	5.17
$m_{ll} < 50$ GeV	19.8	0.181	45.4	2.58	0	0.65
$\Delta\phi_{ll} < 1.3$ rad	18.3	0.168	33.3	2.1	0	0.433
$m_T < m_H$	17.5	0.153	31.5	1.84	0	0.433

Table 6.4: Cross-sections after cuts for different control regions adding the three different channels $e\mu$, ee and $\mu\mu$, under the assumption of a representative Higgs boson mass of 170 GeV applying cuts for the aggressive scenario.

	SR [fb]	WW CR [fb]	Top CR [fb]	W +X CR [fb]	Z +X CR [fb]	$b\bar{b}$ CR [fb]
Signal gg	34.5	1.42	0.26	8.91	1.67	0.06
Signal VBF	0.29	0.007	0.05	0.81	0.01	0.02
$t\bar{t} + Wt$	3.25	19.5	6983	16.7	3.71	9.94
WW	64.4	135	2.39	15.4	30.9	0.30
W +jets	4.16	2.08	935	384	–	2.28
Z +jets	0.43	5.99	42.6	8.28	4725	3.39
WZ	0.86	1.73	0.33	0.44	13.3	0.03
$b\bar{b}$	–	–	–	–	–	44.1
$ZZ+Zb\bar{b}$	–	–	–	–	292.91	–

of the control region boxes. The subsection which follow describe the control samples in more detail and discuss the systematic uncertainties in the extrapolation coefficients α^{XX} (and β^{XX} , where applicable). For convenience, the results are summarised in Tab. 6.8.

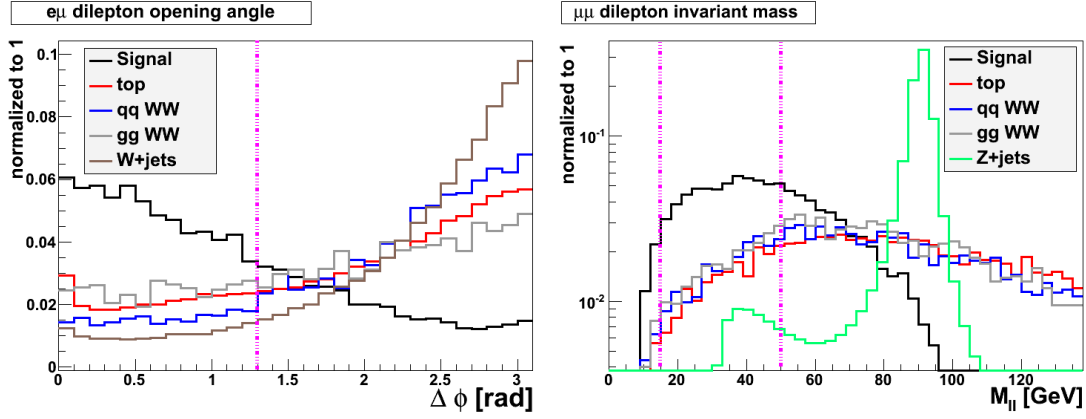


Figure 6.14: Azimuthal separation between the leptons (Left) and invariant mass of the dilepton system (Right) after lepton selection

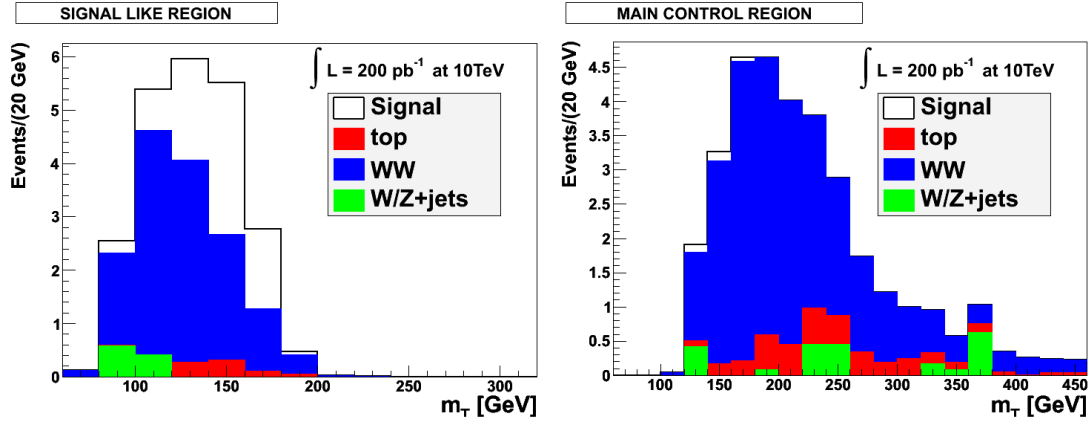


Figure 6.15: Transverse mass distributions for a representative Higgs boson signal (170 GeV) on the top of the main backgrounds for the signal and main control regions for the aggressive scenario.

Normalising Continuum $WW - H \rightarrow WW + 0j$

Following the approach taken in previous studies [27, 67, 103], the present study uses the region with back-to-back leptons (see Figure 6.14) with large dilepton invariant mass to normalise the background arising from continuum W pair production. In particular, the cuts used to select events in this region are the same as in the signal-like region, except:

- the dilepton opening angle in the transverse plane must be larger than 1.3 radians
- the dilepton invariant mass must be larger than 80 GeV. If the leptons have the same flavor and have $|m_{\ell\ell} - m_Z| < 10$ GeV, the event is rejected.
- the transverse mass cut is removed.

 Table 6.5: Continuum WW cross-sections in signal and control region ($e\mu$ channel, in fb) for the different uncertainties choices of Q^2 scale as discussed in Chap. 4; for the aggressive scenario

Mass	central		scale 1		scale 2		scale 3		scale 4	
	SR	CR	SR	CR	SR	CR	SR	CR	SR	CR
120	14.98	81.99	13.38	73.3	16.87	90.18	14.89	80.75	17.27	96.72
130	19.98	81.99	17.92	73.3	22.5	90.18	19.98	80.75	23.16	96.72
140	24.43	81.99	21.97	73.3	27.57	90.18	23.96	80.75	28.31	96.72
150	27.91	81.99	25.28	73.3	31.72	90.18	27.63	80.75	33.17	96.72
160	30.49	81.99	27.63	73.3	34.56	90.18	29.91	80.75	36.65	96.72
165	31.32	81.99	28.49	73.3	35.43	90.18	30.64	80.75	37.92	96.72
170	31.93	81.99	29.22	73.3	35.98	90.18	31.23	80.75	38.8	96.72
180	32.71	81.99	30.03	73.3	36.7	90.18	31.84	80.75	39.97	96.72
190	33.07	81.99	30.41	73.3	37.0	90.18	32.25	80.75	40.56	96.72
200	33.22	81.99	30.55	73.3	37.25	90.18	32.42	80.75	40.93	96.72

 Table 6.6: α^{WW} (ratios of WW cross-sections in signal and control region) for the $e\mu$ channel in the aggressive scenario

Mass	central	scale 1	scale 2	scale 3	scale 4
120	0.182	0.182	0.187	0.184	0.178
130	0.243	0.244	0.249	0.247	0.239
140	0.298	0.299	0.305	0.296	0.292
150	0.340	0.344	0.351	0.342	0.343
160	0.371	0.376	0.383	0.370	0.378
165	0.382	0.388	0.392	0.379	0.392
170	0.389	0.398	0.399	0.386	0.401
180	0.398	0.409	0.407	0.394	0.413
190	0.403	0.414	0.410	0.399	0.419
200	0.405	0.416	0.413	0.401	0.423

Figure 6.15 shows the transverse mass distribution in the signal region (Left) and in this control region (Right). The third column of Tab. 6.4 shows the cross-sections in this region. There is a non-negligible contamination from top and, to a lesser extent, from W and Z +jets. The contribution of the first two backgrounds will be obtained from the control regions described in the following subsections. The contribution from Z +jets will be taken from MC in this study; however, a latter subsection describes a control sample that can be used to check its normalisation in data.

The factor α^{WW} , defined as the ratio of signal region to control region of continuum WW cross-sections is a crucial quantity in this analysis; the uncertainties in its determination propagate

directly into the background uncertainty in the signal region. In the present analysis, the following sources of uncertainty in α^{WW} are considered:

- Theoretical uncertainty, estimated by varying the Q^2 scales by factors of 8 as described in Chapter 4. Table 6.5 shows the cross-sections for $qq \rightarrow WW + gg \rightarrow WW$ for the $e\mu$ channel in the signal region and control region after the distortions are applied. Table 6.6 shows the corresponding values of α^{WW} for the various choices of Q^2 scale; in the $e\mu$ channel, the largest deviation is about 4.8%, and this value is taken to be the uncertainty.⁵
- Jet energy scale uncertainty, estimated by scaling up and down all jet four-vectors and modifying the missing P_T measurement to restore momentum balance. Jet energies are scaled up and down by 7% for jets with $|\eta_j| < 3.2$ and 15% for jets with $|\eta_j| > 3.2$. The missing transverse momentum P_T^{miss} is corrected including a factor extracted from the “Sum E_T ”:

$$\Delta E_T(x) = \pm \alpha E_{\text{jet}}(x), \Delta E_T(y) = \pm \alpha E_{\text{jet}}(y) \quad (6.8)$$

$$\vec{P}_T^{\text{miss}} = \vec{P}_T^{\text{miss}} - \vec{\Delta E}_T \quad (6.9)$$

where

- if $\eta_j < 3.2$ and $E_T^{\text{sum}} < 400$ GeV, $\alpha = 0.06$
- if $\eta_j < 3.2$ and $E_T^{\text{sum}} > 400$ GeV, $\alpha = 0.06 \oplus 0.05 (E_T^{\text{sum}} - 400\text{GeV}) / E_T^{\text{sum}}$
- if $\eta_j > 3.2$ and $E_T^{\text{sum}} < 250$ GeV, $\alpha = 0.06$
- if $\eta_j > 3.2$ and $E_T^{\text{sum}} > 250$ GeV, $\alpha = 0.06 \oplus 0.10 (E_T^{\text{sum}} - 250\text{GeV}) / E_T^{\text{sum}}$

This is done before applying the cuts of the analysis and computing the altered value of α^{WW} . This leads to an uncertainty of about 0.5% in α^{WW} .

- Jet resolution uncertainty, estimated by smearing the jet energies with a Gaussian distribution, and modifying the missing P_T measurement to restore momentum balance before applying the cuts of the analysis and computing the altered value of α^{WW} . The width of the Gaussian distribution depends on the energy and the pseudorapidity of the jet as follows:

$$- \sigma = 0.45\sqrt{E} \text{ if } \eta_j < 3.2$$

⁵Table 6.8 at the end of this section quotes a larger value for the theoretical uncertainty on α^{WW} in the conservative scenario. The reason for this difference is that the tighter cut on the missing transverse momentum in the conservative scenario leads to smaller WW background cross-sections; in that case, the statistical uncertainty due to the finite size of the MC samples used to estimate the theory uncertainty becomes important.

$$- \sigma = 0.63\sqrt{E} \text{ if } \eta_j > 3.2$$

The contribution of the jet resolution uncertainty to the total uncertainty on α^{WW} is only about 0.1%.

- Parton Density Function uncertainties. This source of uncertainty is not considered in the present analysis, since it has been shown to be small in 14 TeV centre-of-mass studies [27, 103].
- The statistical error due to the finite size of the fully simulated MC samples used to estimate the final cross-sections for continuum WW in the signal region and the control region; this leads to a contribution to the uncertainty of 5.64%.

Based on the results obtained after applying the distortions described above, the uncertainty assumed in the significance calculation is 7.4%, obtained by taking the sum in quadrature of the various contributions to the uncertainty. Table 6.8 summarises these numbers as well as the corresponding results for the conservative scenario.

As noted on the $W\gamma$ background is absorbed into the WW background estimate obtained using the WW control region described in this section. The W +jets contribution to the signal region is 1.8 ± 1.04 fb, and the contribution to the WW control region is the same. (The error is the statistical error due to the finite size of the MC sample.) This corresponds to about 5.7% of the WW background in the signal region, and about 2.7% of the WW contribution to the WW control region. If the W +jets contribution to both regions were included in the computation of WW , then the value of this ratio would change by about 3%. Since this is considerably smaller than the systematic error on WW , the W +jets contribution is ignored.

Normalising the top background - $H \rightarrow WW + 0j$

Historically, the most common way to normalise the top background has been to consider b -tagged control samples with the same kinematic cuts as the signal region and the main control region. This strategy has the feature that theoretical uncertainties related to the single-top background cancel out [103], but it is unsuitable in the early data because of the small cross-sections in these control samples.

In the present study, a different strategy is considered: top events are selected in the lepton-hadron channel. This approach assumes that the distributions of the lepton angular variables are known, but still allows the jet veto survival probability to be measured in situ. The event selection for the so-called “top box” control sample consists of the following cuts:

- One lepton, with $P_T > 25$ GeV, passing the same quality and isolation cuts applied for leptons in the signal region.
- Large missing transverse momentum, $P_T^{\text{miss}} > 60$ GeV

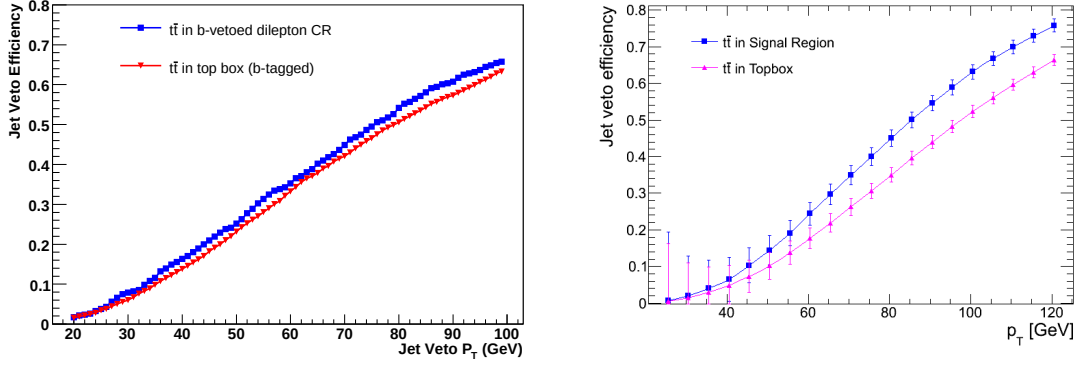


Figure 6.16: Left: a comparison of the jet veto survival probability in the top box and the signal region, when a b -veto is applied in the signal region and a b -tag is applied in the control region. Right: a similar comparison, for the case where a b -veto is not applied in the signal region but a b -tag is applied in the top box.

- At least four jets with $P_T > 20$ GeV in $|\eta| < 4.8$.
- Two of the jets must have SV0 b -tagging weight less than 5.7, and they must add up to the W mass, $70 < m_{jj} < 90$ GeV.
- At least one of the other jets in the event must be b -tagged, with an SV0 weight larger than 5.7.
- Both of the two W candidates (the leptonically decaying one and the hadronically decaying one) are each matched with one of the other jets in the event to form top quark candidates. If there are two b -jets in the event, then both are matched to the W candidates to form the two top candidates according to which pairing gives the best top quark masses (using $m_{top} = 175$ GeV.) If there is only one b -tagged jet, then it is associated to whichever W candidate results in the best top mass, and the other W candidate is matched to whichever other jet leads to the best mass for that top quark candidate. Both top quark candidates are required to have masses larger than 150 GeV.

After this selection is performed, one of the jets is selected to model the jet veto survival probability in the signal region. The procedure for selecting which jet to use is slightly different in the aggressive and conservative scenarios.

In the case of the aggressive scenario, a veto on events where any jet has a large b -tagging weight is applied as a part of the selection which defines the signal region and that this b -tagging veto is applied before the jet veto. This b -tagging weight cut biases the subsequent jet veto survival probability, and this fact must be taken into account when selecting which jet in the top box will be used to model the jet veto in the signal region. For the aggressive cuts,

therefore, the selected jet is the highest- P_T jet in the event excluding the two jets from the decay of the W and the leading b -tagged jet.

Figure 6.16 (Left) shows a comparison between the jet veto survival probability in the signal region as a function of the jet veto P_T threshold and the efficiency obtained when the selected jet is required to have a P_T below the same threshold.⁶ The two curves agree well, indicating that this method is robust for a broad range of jet veto P_T thresholds. For the Conservative Scenario cuts where no b -jet veto is applied in the signal region, the highest- P_T jet is selected after excluding the two jets from the hadronically decaying W . Figure 6.16 (Right) shows the comparison between the jet veto survival probability in the signal region and the estimate obtained using the top box sample and selecting this jet. The two distributions do not agree well for jet veto thresholds above about 30 GeV because the b -tagging requirement in the top box biases the distribution of the leading non- $W \rightarrow qq$ jet. It is therefore necessary in principle to use a top box definition which does not involve b -tagging. However, a careful treatment is necessary to understand the large background from W +jets in the non- b -tagged top box control sample.

Column 4 in Tab. 6.10 shows the cross-section in the top box control region after all cuts except the jet veto. Studies to estimate systematic uncertainties were performed as described in the previous subsection. The total systematic uncertainty for the aggressive scenario is 129%. This value is the sum in quadrature of several sources of error:

- The theoretical uncertainty estimated by varying the factorisation and renormalisation scales in the top background MC by factors of 4 contributes an uncertainty of 75.5%.
- The extrapolation coefficient obtained from a leading-order doubly resonant top MC sample differs from the value obtained from a MC sample which includes the contributions from singly-resonant and non-resonant $WWb\bar{b}$ by as much as 35-40%. Historically [27], this difference has been treated as a systematic uncertainty; the value used here is 40%.
- The jet energy scale uncertainty contributes an error of 47%.
- The jet energy resolution contributes less than 1%.
- The uncertainty in the b -tagging efficiency is estimated by changing the cut on the b -tagging weight so that the b -tagging efficiency changes by 10%. (The nominal cut gives a b -tagging efficiency of 60%, so the altered cuts would have b -tagging efficiencies of 54% and 66%.) This leads to an uncertainty of about 6% in the extrapolation coefficients for the top background.

⁶For historical reasons, this comparisons performed using the IP3D+SV1 [27] b -tagger with a cut of weight >5 defining a b -tagged jet. This tagger is not expected to be available in the early data, but similar results have been obtained using the IP2D tagger, and it is expected that the same result will hold if the SV0 tagger used throughout the rest of this Section would be used for this exercise.

- The finite size of the MC samples used for the final cross-sections leads to a statistical uncertainty of 85%.

It is worth noting that some of the values quoted here, notably the theoretical uncertainties and the jet energy scale uncertainty, may be enhanced due to the finite size of the MC samples used to evaluate them. However, since these samples represent effective luminosities well in excess of 200 pb^{-1} , the quoted uncertainties are taken at face value in the present study. Table 6.8 summarises these results, shows the systematic uncertainties in the extrapolation ratio between the control region used to normalise WW and the top control sample, and gives the corresponding results for the conservative scenario.

Normalising W +jets - $H \rightarrow WW + 0j$

To normalise the W +jets background, a control sample is defined by selecting events where one of the electrons is required to satisfy a loosened identification condition. The event is required to be an $e\mu$ candidate, and the electron is required to satisfy the standard ATLAS “Loose” identification condition and not to satisfy the “Tight” electron identification cut. (Events with two electrons or two muons are not considered in this control sample for the present study.) The other cuts for this control sample (in particular the lepton isolation cuts) are the same as for the signal region. The cross-sections after these cuts for various processes are shown in the fifth column of Tab. 6.10; clearly, this control sample is a very pure W +jets region.

In order for a control sample like this to yield a more convincing background estimate than MC, one must devise a way to extract α^{W+jets} (ratio of W +jets cross-sections in the signal region and this control region) from data. The approach used here is to take this ratio from a control sample comprised of γ +jets events. The expected algorithmic uncertainty on the extrapolation of the W +jets background normalisation from the loose-identification control region to the signal region in 200 pb^{-1} of integrated luminosity is 10%.

The present study considers two additional sources of uncertainty:

- The jet energy scale and resolution uncertainties are estimated using the same procedure as was used in the cases of WW and top. However, no MC events remain in the signal region for aggressive scenario, so no uncertainty can be computed there. In the case of the extrapolation to the control region in the aggressive scenario, the jet energy scale uncertainty is found to be about 2.7%.
- The MC statistical uncertainty on the extrapolation from the W +jets control region to the WW control region is about 100%.

At first glance, one may wonder how the systematic error from the jet uncertainties can be so small when the MC statistical error is so large. The reason for this unusual outcome is

that there is only one W +jets MC event remaining in the large- $\Delta\phi_{\ell\ell}$ region used to normalise the WW background, but there are a large number of MC events remaining in the reversed-identification region used to normalise W +jets. When the jet measurements were distorted for the systematic check on the jet energy scale, it happened that the event in the large- $\Delta\phi_{\ell\ell}$ region still passed the cuts, but the cross-section in the W +jets control region changed by a (well-determined) few percent.

These contributions to the uncertainty, as well as the corresponding results for the conservative scenario cuts, are summarised in Tab. 6.8 at the end of this section.

Checks to normalise the Z +jets contribution - $H \rightarrow WW + 0j$

Z +jets events with fake missing transverse energy constitute a dangerous background in the same flavor channels. A tight requirement on the Missing P_T suppresses Z +jets by a large factor in the analysis. However, even though the MC prediction of the effective cross-section after cuts is small, it is nevertheless important to demonstrate that the cut actually performs as expected in data.

The control region is defined based on the Z peak. Events with two leptons are selected as in the signal region, and the following cuts are applied:

- $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$
- $\Delta\phi_{\ell\ell} > 2.0$
- The same jet veto that is applied in the signal region is applied here as well.
- A lower bound on the missing transverse energy. The effective cross-section in this control region is studied as a function of the value of this cut, which ranges from zero to the requirement in the signal region.

Table 6.10 gives the expected cross-sections in the Z peak control sample before the application of the missing P_T cut, and Table 6.7 shows the cross-sections for several values of the cut on the P_T^{miss} .

The left plot in Figure 6.28 shows this cross-section information in a graphical format; the red curve is Z +jets and the blue curve is the other backgrounds. The right plot shows the ratio of the Z +jets cross-section in the signal region divided by the Z +jets cross-section in the control region. The ratio is fairly flat, indicating that if the diboson contamination is understood, the Z +jets cross-section can be controlled using this sample.

However, it is important to note that as the missing P_T cut increases, the relative contribution from other processes increases as well. This contribution is shown as the blue curve in the left plot of Figure 6.28; for tight values of the P_T^{miss} cut it is comparable to the Z +jets contribution.

Table 6.7: Cross-sections (in fb, summed over lepton flavor) for several physics processes in the Z control sample described in Sec. 6.2.5, for several values of the cut on missing P_T .

MET cut(GeV)	Signal	WW	$t\bar{t} + Wt$	WZ + ZZ	$Zb\bar{b}$	Z+jets
0	1.67	31.52	3.71	30.76	275.41	4725.09
10	1.67	31.39	3.64	29.89	239.19	3962.91
20	1.63	30.36	3.51	27.01	52.63	582.82
25	1.61	28.42	3.51	25.42	18.36	141.90
30	1.39	25.55	3.16	23.72	5.73	38.87
35	1.21	21.89	2.91	21.18	1.38	11.92
40	0.90	17.28	2.35	18.19	0.40	3.40

If not properly subtracted, this contribution may cause the estimated Z+jets cross-section in the signal region to have a slight upwards bias; however, since the Z+jets cross-section in the signal region is expected to be negligibly small, the present study makes no attempt to reduce this bias.

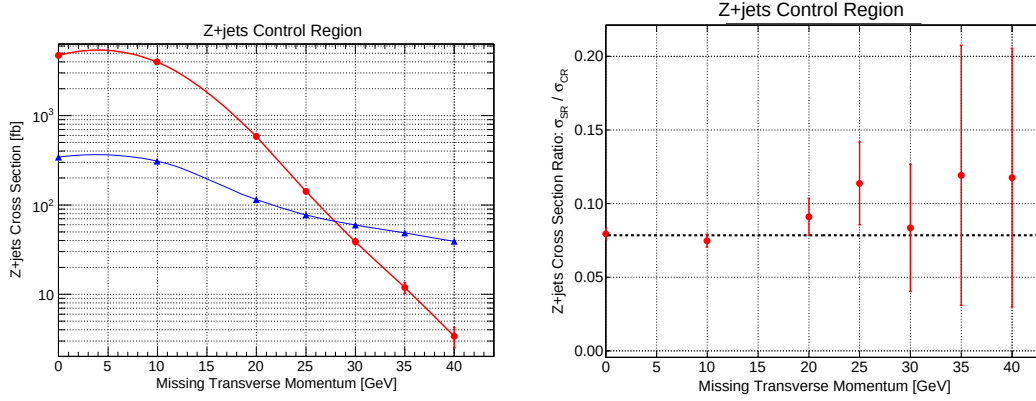
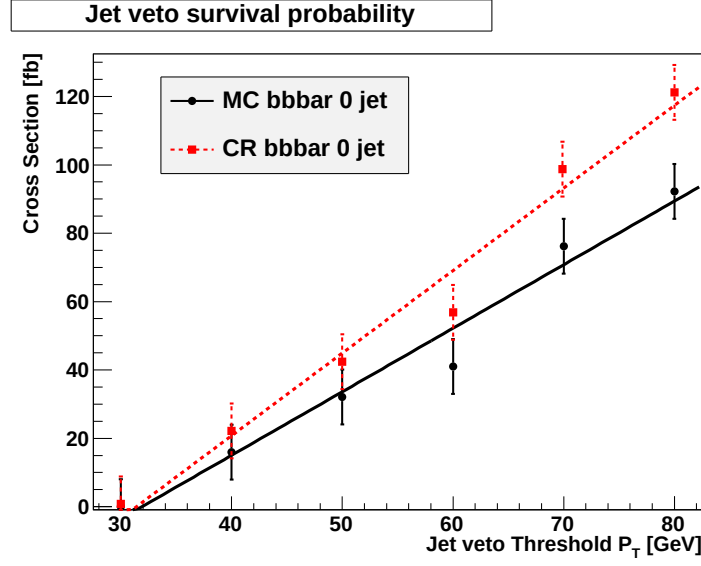


Figure 6.17: Left: the cross-sections for Z+jets and the various other contributions to the control region described in Subsec. 6.2.5, as functions of the cut on the missing P_T . Right: the ratio of the Z+jets cross-section in the signal region to the Z+jets cross-section in the control region of Sec. 6.2.5, as a function of the missing P_T cut applied in both regions.

Checks to normalise the $b\bar{b}$ background - $H \rightarrow WW + 0j$

The $b\bar{b}$ background is a potentially dangerous background because of its large cross-section. With the currently available MC samples, it is reduced to negligible levels by the lepton P_T cuts, the isolation cuts and the missing P_T cut. However, it is possible that this background might give a larger than expected contribution due, for example, to jets which carry large missing P_T down the beam pipe [99]. It is therefore important to have a technique ready to normalise this background in situ.


 Figure 6.18: Cross-section as a function of jet P_T threshold in the $b\bar{b}$ control region

The strategy employed here is to select events for which the impact parameter significance of the leptons is large (> 3 for muons, > 6 for electrons). Figure 6.29 shows that in the absence of a jet veto, the cross-section for $b\bar{b}$ in this region is large and the cross-section for other backgrounds is small. By way of comparison, Table 6.10 shows that the MC $b\bar{b}$ background is reduced to zero with the jet veto proposed in the present analysis.

Figure 6.29 shows the cross-section as a function of the jet veto P_T threshold;⁷ in data, one can vary the jet veto P_T threshold in the reversed-impact-parameter region and observe that the number of surviving $b\bar{b}$ events drops off as the jet veto threshold becomes small. The figure also shows that one can verify, using a similar selection of events with a reversed cut on missing $P_T < 30$ GeV that the $b\bar{b}$ cross-section in the region with normal isolation and impact parameter cuts is smaller than the corresponding cross-section in the region with reversed impact parameter cuts and no isolation cuts. Thus, the full set of control samples are sufficient to prove using data that the $b\bar{b}$ is negligibly small; if it is not negligibly small, then further work will need to be done to assess the systematic error on the resulting estimate of the $b\bar{b}$ normalisation.

⁷Note that the error bars in this plot are correlated, since all the events that pass a jet veto with a given threshold will also pass a jet veto cut with a higher threshold.

Table 6.8: Systematic uncertainties for the different extrapolation ratios in the aggressive scenario, the conservative scenario in the $H \rightarrow WW + 0j$ search.

Aggressive Scenario					
	α^{WW}	α^{Top}	α^{Wjets}	β^{Top}	β^{Wjets}
Q^2	4.87%	75.47%	–	8.88%	0.00%
Jet Scale Up	0.44%	25.55%	–	23.47%	0.68%
Jet Scale Down	0.27%	46.66%	–	45.83%	2.71%
Jet Resolution	0.10%	0.14%	–	0.12%	0.00%
b -tagging eff.	0.08%	5.59%	–	4.65%	0.00%
Wt	0.00%	40.00%	–	40.00%	0.00%
MC Statistics	5.64%	84.58%	–	10.48%	100.4%
Total	7.47%	129.1%	–	62.53%	100.4%
Conservative Scenario					
	α^{WW}	α^{Top}	α^{Wjets}	β^{Top}	β^{Wjets}
Q^2	15.78%	30.20%	0.00%	7.90%	–
Jet Scale Up	0.80%	46.66%	7.41%	41.10%	–
Jet Scale Down	0.88%	42.44%	9.45%	38.44%	–
Jet Resolution	0.00%	0.14%	0.99%	0.11%	–
b -tagging eff.	0.11%	12.24%	0.00%	11.10%	–
Wt	0.00%	40.00%	0.00%	40.00%	–
MC Statistics	12.48%	41.14%	101.5%	6.74%	–
Total	20.14%	80.81%	102.0%	59.33%	–

Results for $H \rightarrow WW + 0j$

Figure 6.19 shows the expected Bayesian and Frequentist upper bounds on the Higgs boson cross-section as a function of mass using the “aggressive” and “conservative” scenarios, assuming an integrated luminosity of 200 pb^{-1} and a centre-of-mass energy of 10 TeV. There is a significant probability to exclude a small region around $m_H = 160 \text{ GeV}$. Figure 6.31 shows the expected Frequentist upper bound at this centre-of-mass energy for several different values of the integrated luminosity. With an integrated luminosity between 500 pb^{-1} and 1 fb^{-1} , it is possible to exclude a broad range of Higgs boson masses.

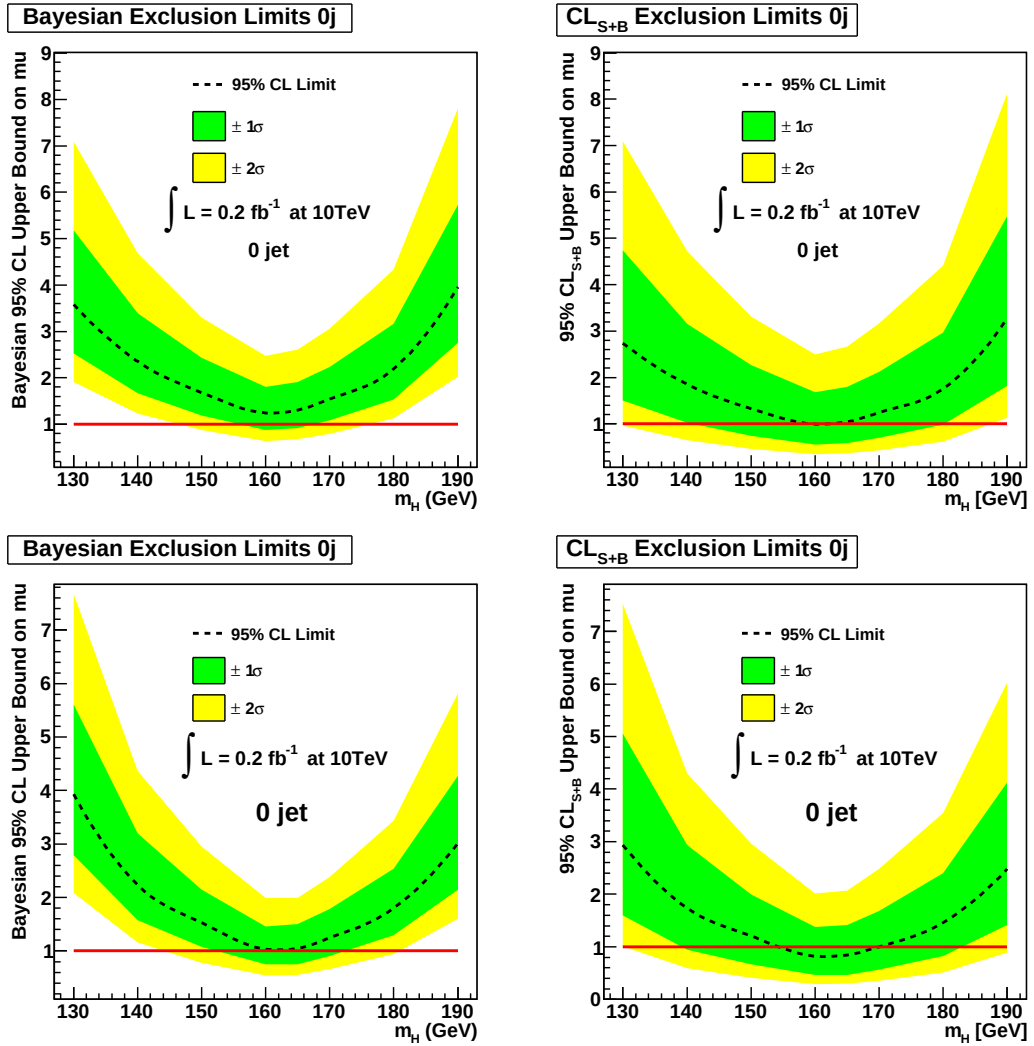


Figure 6.19: Bayesian and Frequentist 95% CL Upper-bound on μ , at $\sqrt{s} = 10 \text{ TeV}$ and 200 pb^{-1} of integrated luminosity for aggressive (top) and conservative (bottom) scenarios.

The signal significance is estimated based on the Likelihood Ratio for $\mu = 0$. The p -value

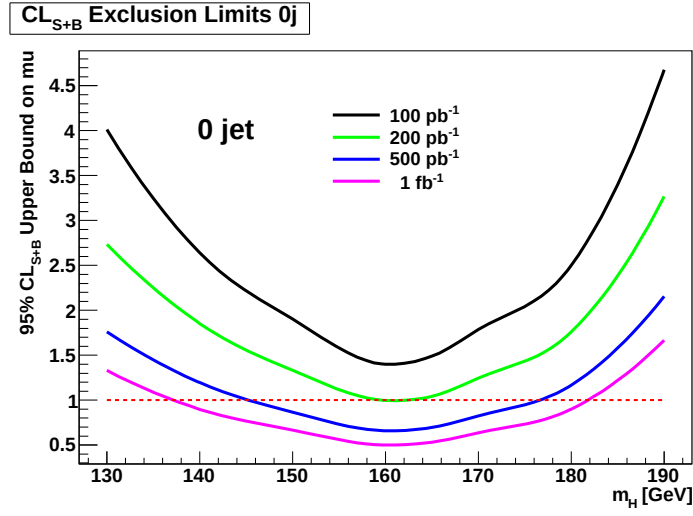


Figure 6.20: Comparisons at different luminosities in the aggressive scenario.

is obtained by first finding the median of the distribution of $\lambda(\mu = 0)$ in a sample of toy MC outcomes with $\mu = 1$, and then integrating the distribution for background-only ($\mu = 0$) outcomes from this value to infinity. Again, since the significance is only about 1.7σ for $m_H = 160$ GeV, it is not appropriate to show a plot of the expected significance.

PDF Reweighting, sensitivity at 7 TeV - $H \rightarrow WW + 0j$

The reweighting method explained in detail in Chap. 4, allows the estimation of sensitivity when running at a different centre-of-mass energy than the one used for the original MC production. Appendix. A.2 also includes a validation of the results of the re-weighting method which consists of a comparison between the re-weighted results and the results of full matrix element calculations using HIGLU, VV2H and MCFM. Figure 6.21 shows the exclusion limits ATLAS would expect to reach running at 7 TeV if 200 pb^{-1} integrated luminosity are collected and the three channels ($e\mu$, ee and $\mu\mu$) are combined.

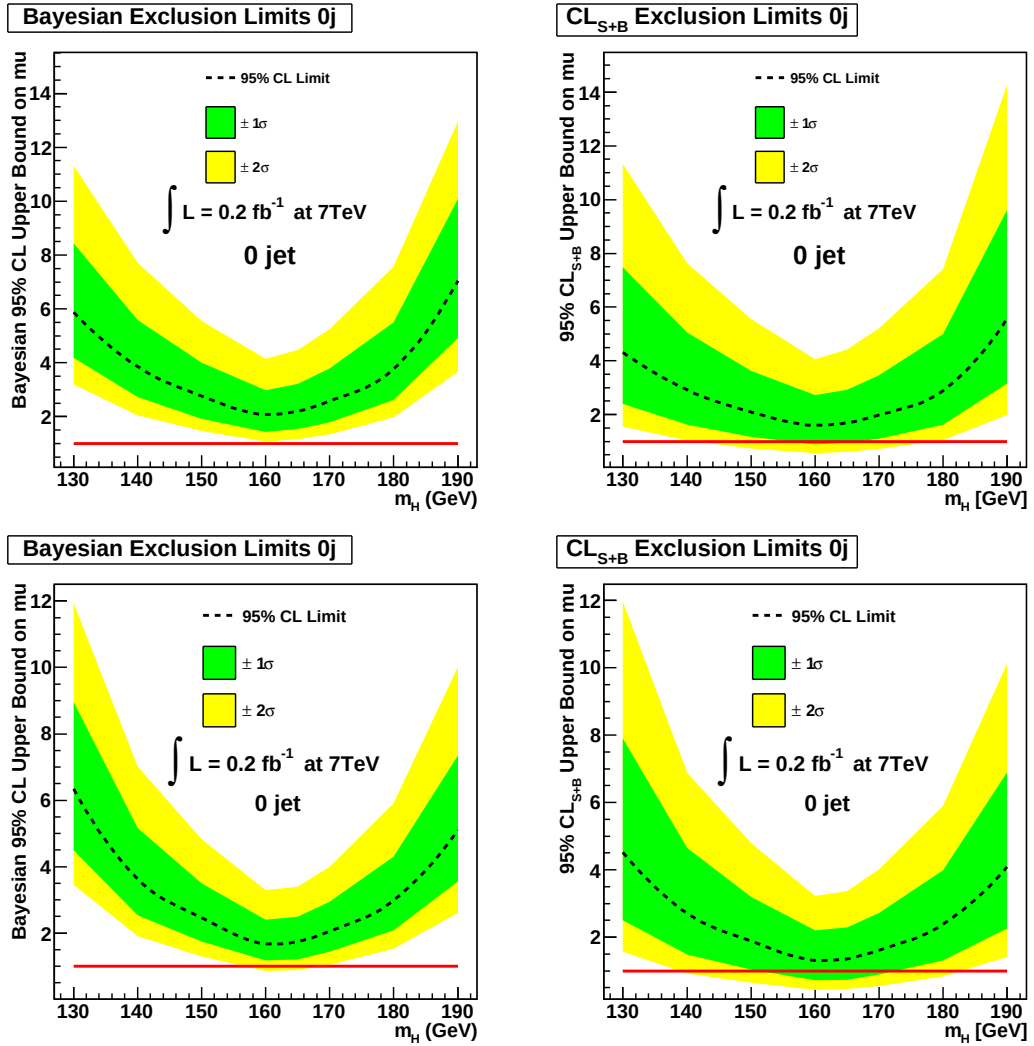


Figure 6.21: Bayesian and Frequentist 95% CL Upper-bound on μ , at $\sqrt{s}=7$ TeV with 200 pb^{-1} of integrated luminosity for aggressive (top) and conservative (bottom) scenarios.

The $H \rightarrow WW + 0j$ analysis was re-optimised for studies on the early LHC data. Two vari-

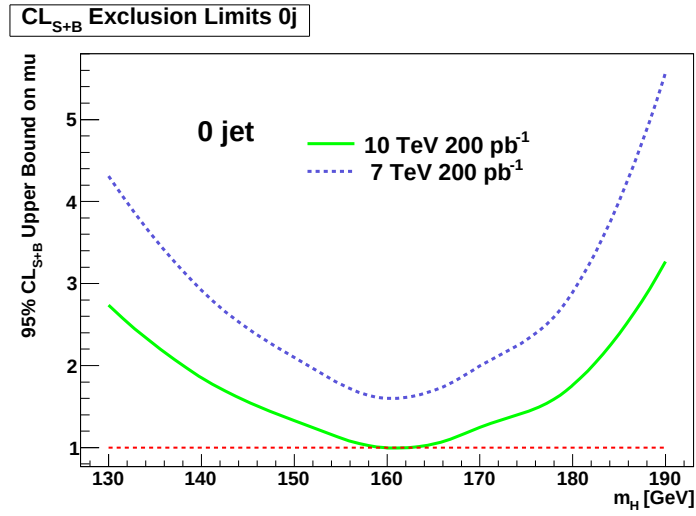


Figure 6.22: Comparisons at different centre-of-mass of energy in the aggressive scenario

ants of the analysis appropriate for different detector performance scenarios were proposed. The analysis includes a complete set of control samples, as well as detailed studies of the systematic errors (from both theoretical and experimental sources) on each of the background determinations. With only 200 pb⁻¹ of integrated luminosity at a 10 TeV centre-of-mass energy, there is a significant probability to exclude a small range of the Standard Model Higgs boson mass around 160 GeV.

6.2.6 1 jet

The search for $H \rightarrow WW$ decays in association with one hard jet (see Fig. 6.23) has been studied previously for $\sqrt{s} = 14$ TeV and $\int \mathcal{L} dt = 10 \text{ fb}^{-1}$ in [135] and systematic uncertainties in the background normalisation were found to be a serious concern for the analysis. However, in the early data, it is reasonable to expect that statistical errors will be dominant; it is therefore of interest to investigate the potential for a search for $H \rightarrow WW$ in association with one hard jet in the first few hundred pb^{-1} of integrated luminosity.

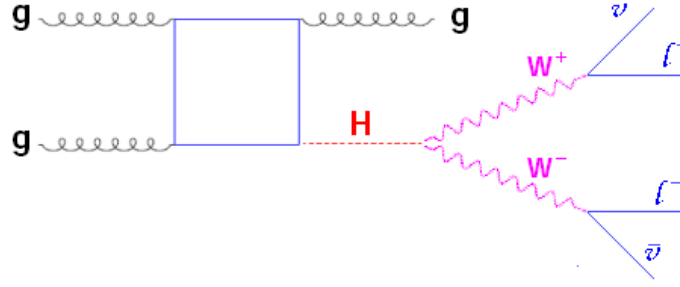


Figure 6.23: One of the Feynman diagrams for gluon-gluon fusion Higgs boson production associated with a hard jet

Events in the one jet category are selected based on the following criteria:

- Events are required to contain a hard jet with $P_T > 20 \text{ GeV}$ and $|\eta| < 3$; this jet is referred to as the “tagged” jet. Jets are reconstructed from topological clusters using a cone algorithm with a radius of 0.4.
- A jet veto is applied to reject any event with a second hard jet in $|\eta| < 3$.
- A b -jet veto is applied to the remaining jets. If any jet has $P_T > 15 \text{ GeV}$ and an SV0 weight greater than 5.7, the event is rejected.
- The transverse momentum of the vectorial addition of the dilepton system plus the missing energy plus the tagged jet must be smaller than 30 GeV. Figure 6.24 shows that this is an effective cut to reduce top background.

The subsequent topological requirements of the rejection of the $Z \rightarrow \tau\tau$, the dilepton opening angle in the transverse plane, and the transverse mass upper bound are then applied. Table 6.9 shows the cutflow for the $e\mu$ channel for a representative Higgs boson mass of 170 GeV in the aggressive scenario. Cutflow tables for ee and $\mu\mu$ channels, as well as all the corresponding tables for the conservative scenario and tables showing the cross-sections after all cuts for each Higgs boson mass hypothesis, are shown in Appendix A.8.1.

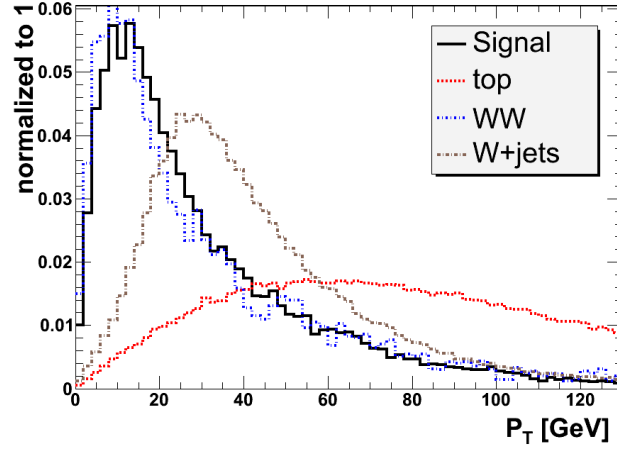

 Figure 6.24: p_T of the vectorial sum of leptons, p_T^{miss} and the tagged jet.

 Table 6.9: Cutflow for the $e\mu$ channel, for a representative Higgs boson mass of 170 GeV, in the aggressive scenario.

Cut	$gg \rightarrow H$	VBF	WW	$t\bar{t} + Wt$	$W+\text{jets}$	$Z+\text{jets}$
2 Leptons	83.3	12.2	567	3867	79.3	2447
$m_{\ell\ell} > 15 \text{ GeV}$	80.2	11.9	560	3836	68.6	2441
$p_T^{\text{miss}} > 30 \text{ GeV}$	72.1	10.5	396	3267	48.1	230
$m_T^{\ell\nu} > 30 \text{ GeV}$	71.0	9.95	375	2842	47.1	50
Jet acceptance	25.0	2.39	105	285	22.1	27.0
b -jet veto	24.4	2.31	101	120	22.1	23.0
$p_T^{\text{tot}} < 30 \text{ GeV}$	22.2	2.13	93.1	90.9	21.0	22.2
$Z \rightarrow \tau\tau$ rejection	22.0	2.09	89.4	85.0	18.9	4.44
$m_{\ell\ell} < 50 \text{ GeV}$	13.3	1.31	18.4	14.5	2.11	4.04
$\Delta\phi_{\ell\ell} < 1.3 \text{ rad}$	11.7	1.17	12.8	11.6	1.05	0
$m_T < m_H$	11.0	1.09	12.2	9.84	1.05	0

A cut on the pseudorapidity of the leading jet, $|\eta_j| > 1.8$, which was applied in the analysis of Ref. [135], is not used in this analysis. Figure 6.25 shows the distribution of this variable. The plot confirms that it contains discriminating power; however, this cut decreases the signal acceptance significantly. Given the small number of signal events expected in 200 pb^{-1} of integrated luminosity, it is advantageous to remove this cut. Moreover, as will be shown in a following Subsection, the presence of this cut significantly increases the theory uncertainty.

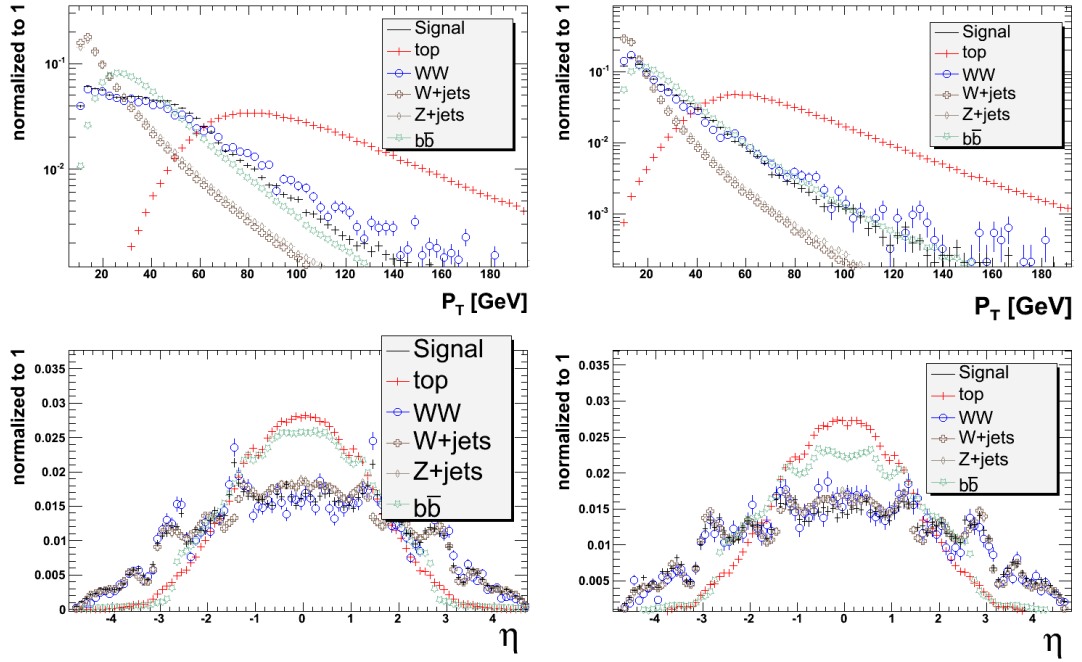


Figure 6.25: Jet kinematics for signal and main backgrounds. Left: P_T and η for the leading jet. Right: P_T and η for the subleading jet.

The cross-sections after all cuts using the aggressive scenario are shown in Tab. 6.10; Figure 6.26 shows the transverse mass distribution for signal on top of background for a representative Higgs boson mass of 170 GeV.

Control Samples and Systematics for $H \rightarrow WW + 1j$

A quick glance at the second column of Tab. 6.10 reveals that the main backgrounds are continuum WW , top, and W +jets, and Z +jets. The estimation of the normalisation of these backgrounds is the focus of this Subsection.

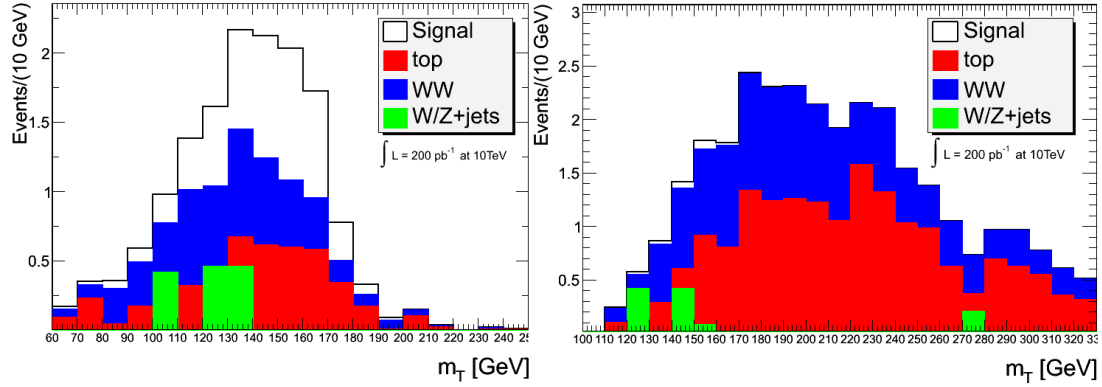


Figure 6.26: Transverse mass distribution, signal on the top of main backgrounds, for a representative Higgs boson mass of 170 GeV in the aggressive scenario. Left: the distribution in the signal region. Right: the distribution in the main control region.

Table 6.10: Cross-sections after cuts for different control regions adding the three different channels $e\mu$, ee and $\mu\mu$, using the aggressive scenario.

	SR [fb]	WW CR [fb]	b -tag CR [fb]	W+X CR [fb]	Z+X CR [fb]	$b\bar{b}$ CR [fb]
$gg \rightarrow H$	23.2	1.12	0.73	2.75	1.33	0.12
VBF	2.18	0.09	0.15	0.352	0.10	0.04
$top \ i\bar{i} + Wt$	19.9	102	94.6	5.1	20.8	27.1
WW	24.6	70.4	1.17	5.57	18	0.35
W +jets	2.11	5.28	–	293	6.57	6.76
Z +jets	2.76	0.42	0.07	0.829	18204	6.57
WZ	0.78	2.28	0.002	0.14	18.9	0.02
$b\bar{b}$	–	–	–	–	8.02	136

Normalising Continuum $WW - H \rightarrow WW + 1j$

The largest contribution to the background in the signal region comes from continuum WW events, including $qq \rightarrow WW$, $qg \rightarrow WW$, and $gg \rightarrow WW$ with one high P_T jet. In practice, it is not possible to distinguish these backgrounds from each other, so they must be treated together. Following the strategy outlined in previous work (Refs. [135] and, more recently, Ref. [27]), the approach considered here is to count events in the region where the leptons are back-to-back ($\Delta\phi_{\ell\ell} > 1.3$), where they have large invariant mass ($m_{\ell\ell} > 80$ GeV), and where the transverse mass cut has been removed. The other cuts of the analysis are the same as in the signal region.

The third column in Tab. 6.10 shows the cross-sections for the signal and various backgrounds in this region. The contributions from top, W +jets, and Z +jets are all non-negligible. The normalisation of Z +jets with $Z \rightarrow \ell\ell$ ($\ell = e/\mu$) can be controlled using the approach described latter in this section. The contribution from $Z \rightarrow \tau\tau$ can be well-understood using the embedding method with $Z \rightarrow \mu\mu$ events. The W +jets and top normalisations can be estimated using the control samples presented in the next two Subsections.

Table 6.11: Ratios of WW cross-sections in signal and WW control region, $e\mu$ channel, in the aggressive scenario

mass	$qq + qg + gg$					$qq + qg$ only				
	central	scale1	scale2	scale3	scale4	central	scale1	scale2	scale3	scale4
120	0.153	0.153	0.136	0.161	0.142	0.151	0.144	0.136	0.158	0.142
130	0.195	0.204	0.183	0.206	0.186	0.191	0.188	0.183	0.203	0.185
140	0.240	0.250	0.220	0.246	0.223	0.233	0.226	0.220	0.241	0.222
150	0.272	0.290	0.255	0.284	0.257	0.262	0.256	0.255	0.276	0.255
160	0.302	0.321	0.285	0.310	0.284	0.288	0.277	0.284	0.300	0.282
165	0.313	0.334	0.295	0.320	0.292	0.297	0.286	0.294	0.309	0.290
170	0.321	0.345	0.303	0.329	0.300	0.304	0.294	0.302	0.317	0.297
180	0.331	0.358	0.311	0.339	0.310	0.312	0.302	0.310	0.326	0.308
190	0.339	0.365	0.315	0.344	0.315	0.318	0.306	0.314	0.331	0.313
200	0.342	0.369	0.317	0.347	0.318	0.321	0.309	0.317	0.334	0.316

Table 6.12: Fractional deviation of α^{WW} from the central value, with and without the gg contribution on the WW background, in the aggressive scenario.

mass	$qq + qg + gg$				$qq + qg$ only				$\Delta w/w.o\ gg$
	$\Delta scale1$	$\Delta scale2$	$\Delta scale3$	$\Delta scale4$	$\Delta scale1$	$\Delta scale2$	$\Delta scale3$	$\Delta scale4$	
120	0.999	1.125	0.953	1.076	1.050	1.112	0.956	1.067	0.989
130	0.954	1.068	0.945	1.051	1.017	1.048	0.944	1.036	0.982
140	0.962	1.093	0.976	1.076	1.034	1.061	0.969	1.049	0.970
150	0.938	1.066	0.959	1.061	1.023	1.025	0.949	1.025	0.961
160	0.942	1.061	0.976	1.066	1.038	1.012	0.960	1.022	0.952
165	0.935	1.061	0.979	1.070	1.037	1.009	0.962	1.023	0.949
170	0.930	1.060	0.977	1.071	1.033	1.005	0.958	1.021	0.946
180	0.926	1.067	0.978	1.069	1.034	1.006	0.957	1.014	0.941
190	0.927	1.075	0.983	1.074	1.038	1.012	0.962	1.017	0.939
200	0.927	1.079	0.985	1.075	1.039	1.014	0.963	1.017	0.938

There is considerable uncertainty on α^{WW} , the ratio of continuum WW cross-sections in the signal region and this control region. As in the previous analysis of this channel, the generator used to model the $gg \rightarrow WW$ process [97] only includes leading order ($\mathcal{O}(\alpha_s^2)$) matrix elements, and it is again the case that the leading jet in the presently available $gg \rightarrow WW$ MC sample is produced by a parton showering algorithm. Thus, a systematic error derived from the usual variation of Q^2 scales is not fully convincing by itself. Table 6.11 shows the ratio of cross-sections in the signal region and the control region with various altered MC configurations. The second column shows the baseline, computed from the sum of $qq \rightarrow WW$, $qg \rightarrow WW$ and $gg \rightarrow WW$ contributions. The next four columns show the corresponding results using MC samples with the factorisation and renormalisation scales altered by factors of 8; the exact definitions of scale 1, scale 2, etc. are given in Chapter 4. The next five columns show the corresponding results derived by using only the MC@NLO samples, i.e. ignoring the $gg \rightarrow WW$ contribution completely. The difference of these ratios is taken as the source of theory systematic uncertainty for the extrapolation ratio, they are shown in Tab. 6.12, where the difference between the baselines values is also shown in column 10.

Among the results with all the altered MC configurations, the largest deviation of the ratio from the baseline is 12.5%, and the largest deviation due the inclusion of the $gg \rightarrow WW$ process is $< 7\%$. Since the latter is considerably smaller than the uncertainty caused by the Q^2 alteration, the theoretical uncertainty in α^{WW} is taken to be 12.5%, the value from the Q^2 scale alterations.

Uncertainties due to the jet energy resolution and jet energy scale are studied following the prescription described in the zero jet Subsection 6.2.5. This prescription is recommended procedure for handling these uncertainties in ATLAS at the time of writing of this analysis.

The jet energy scale variation is performed by scaling each jet's energy and momentum up and down by 7 and 15% for jets with $|\eta| < 3.2$ and $|\eta| > 3.2$, respectively. A correction on the missing energy is performed with a binning dependency on E_T^{sum} Table 6.13 shows the ratios of cross-sections and their fractional deviation from the nominal value.

mass	Baseline	Scale Up	Scale Down	Frac. Dev. (Up)	Frac. Dev. (Down)
120	0.153	0.153	0.152	0.998	1.005
130	0.195	0.197	0.199	0.990	0.980
140	0.240	0.239	0.244	1.005	0.985
150	0.272	0.272	0.277	1.000	0.984
160	0.302	0.301	0.305	1.005	0.990
165	0.313	0.312	0.318	1.002	0.984
170	0.321	0.321	0.325	1.000	0.986
180	0.331	0.331	0.337	1.002	0.983
190	0.339	0.338	0.345	1.002	0.982
200	0.342	0.342	0.349	1.002	0.982

Table 6.13: Extrapolation ratios for nominal case and the cases where the jet energy scale is shifted up and down, as well as the fractional deviations of the altered cases from the nominal values, for the $e\mu$ channel.

As was done in the zero jet analysis, the systematic errors arising from parton density function uncertainties are ignored.

The sum in quadrature of the various uncertainties that are expected to affect the predicted value of α^{WW} is about 16.5%; the second column in Tab. 6.8 gives details of the different values that come into this estimation, for the aggressive and conservative scenarios.

Normalising Top - $H \rightarrow WW + 1j$

Following the treatment presented in previous studies [135], the top background can be normalised using a control sample defined by the requirement that events contain a b -tagged jet. The event selection for this region requires at least one b -jet with an SV0 weight larger than 5.7; the other cuts are the same as in the signal like region with the exception that the transverse mass window is removed. Table 6.10 shows the cross-sections of the various contributions to this region; there is very little contamination from processes other than top.

This b -tagged control region is used to estimate the number of top events in both the signal region and the WW control region. The number of observed events in the b -tagged region is multiplied by a constant denoted as α^{Top} for the signal region or β^{Top} for the WW control region to obtain the expected contribution from top background. There are several sources of uncertainty relevant to these ratios:

- The b -tagging efficiency is expected to be known to within 10%. [27] The procedure to assess the impact of this uncertainty on the background determination is the same as in the zero jet bin; the result for this channel (in the aggressive scenario) is about 21% for α^{Top} and about 16% for β^{Top} .
- The jet energy scale and resolution contribute about 16% for α^{Top} and about 9.5% for β^{Top} .
- The statistical error due to the finite size of the available MC samples is about 21% for α^{Top} and about 6.3% for β^{Top} .

Table 6.14 shows the extrapolation ratios and their uncertainties for α^{Top} in the aggressive and conservative scenarios. The uncertainties, along with the corresponding results for β^{Top} are also summarised in Tab. 6.8.

Normalising W +jets - $H \rightarrow WW + 1j$

The W +jets background normalisation represents a crucial part of this analysis. Although its contribution is expected to be small, the large cross-section and the difficulty associated with obtaining a convincing estimate of the fake rate make it a dangerous background nevertheless. These difficulties are compounded by a lack of MC statistics; out of almost 10M fully simulated

mass	Aggressive Scenario						
	Baseline	Scale Up	Scale Down	b -Tagging	Δ (Up)	Δ (Down)	Δ (b -Tag)
120	0.045	0.051	0.039	0.057	0.878	1.160	0.793
130	0.060	0.066	0.055	0.076	0.910	1.092	0.791
140	0.075	0.082	0.068	0.095	0.920	1.106	0.795
150	0.096	0.102	0.087	0.120	0.948	1.112	0.805
160	0.112	0.116	0.102	0.139	0.960	1.096	0.804
165	0.117	0.125	0.108	0.147	0.941	1.087	0.801
170	0.121	0.129	0.112	0.151	0.940	1.076	0.802
180	0.127	0.136	0.117	0.160	0.932	1.084	0.795
190	0.131	0.139	0.121	0.165	0.945	1.083	0.796
200	0.132	0.140	0.123	0.166	0.941	1.078	0.796

mass	Conservative Scenario						
	Baseline	Scale Up	Scale Down	b -Tagging	Δ (Up)	Δ (Down)	Δ (b -Tag)
120	0.043	0.048	0.042	0.059	0.879	1.019	0.718
130	0.060	0.065	0.058	0.081	0.915	1.037	0.740
140	0.086	0.095	0.083	0.116	0.904	1.035	0.742
150	0.126	0.133	0.125	0.166	0.948	1.008	0.760
160	0.160	0.164	0.159	0.211	0.976	1.011	0.762
165	0.174	0.179	0.172	0.227	0.968	1.012	0.764
170	0.185	0.190	0.183	0.241	0.974	1.010	0.767
180	0.201	0.209	0.199	0.264	0.961	1.010	0.762
190	0.209	0.215	0.207	0.273	0.971	1.010	0.763
200	0.212	0.219	0.211	0.279	0.971	1.007	0.762

Table 6.14: Top extrapolation ratios for the nominal case, the cases with the jet energy scale shifted up and down, and an altered b -tagging performance scenario. The columns labelled “ $\Delta(X)$ ” show the fractional change of each of the altered cases with respect to the nominal case. All numbers are for the $e\mu$ channel.

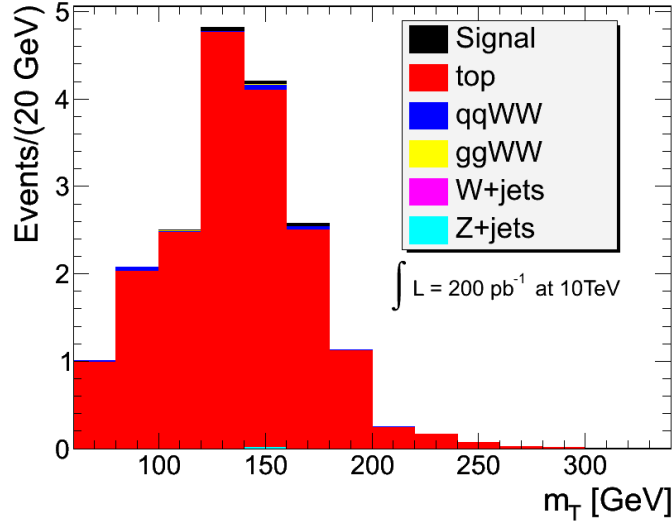


Figure 6.27: Transverse mass distribution, in the b -tagged control region

events, only a few survive all the cuts of the signal region. This implies statistical uncertainties in the neighbourhood of 100%.

The W +jets background in the signal region is normalised using a control sample with reversed electron identification cuts; a loosened or reversed muon selection has not been considered here since the fake rate for electrons is expected to be larger than the fake rate for muons.

Events are required to have one isolated muon and one isolated electron which satisfies the “Loose” isEM requirement but not the “Tight” requirement. The veto against events with two hard jets is relaxed, but a b -veto to reduce top is still applied. The other cuts, such as P_T^{miss} , $m_{\ell\ell}$, and isolation, are the same as in the signal region.

Methods to estimate the extrapolation coefficients from this control region to the signal region and the WW control region, $\alpha^{W \text{ jets}}$ and $\beta^{W \text{ jets}}$ respectively, were also investigated. Based on that study, it is assumed that both $\alpha^{W \text{ jets}}$ and $\beta^{W \text{ jets}}$ can be estimated with an accuracy of about 10% using a control sample consisting of γ +jets events. Detector uncertainties, like jet energy scale and resolution, are calculated following the same procedures described in Subsection 6.2.5 and also used in sections 6.2.6 and 6.2.6; the results are summarised in Tab. 6.8.

The dominant uncertainty in the normalisation of this background is poor MC statistics in the prediction of $\alpha^{W \text{ jets}}$ and $\beta^{W \text{ jets}}$. With real data in hand, it may not be necessary to include this as an uncertainty, since there can be an in-situ estimate of the extrapolation coefficients. However, for the purposes of a MC prediction, the present study uses this uncertainty in lieu of the algorithmic uncertainty quoted above.

Although there is a large uncertainty on its determination, this background is expected to give a relatively small contribution to the signal region (about 10%; see Tab. 6.10); the main task in data is to prove that its normalization is not significantly larger than expected.

Checks to normalise the Z +jets contribution - $H \rightarrow WW + 1j$

The Z +jets contribution in the signal region is expected to be small, but this statement relies on a strong suppression of this background using a cut on the missing transverse momentum. Z +jets is therefore a dangerous background in the same sense as W +jets, and it is desirable to have a means to check in data that its normalisation is not significantly larger than expected.

Following the same procedure described in the Z +jets the control region for the zero jet case, the sample is built based on a Z peak reconstruction: Table 6.10 gives the expected cross-sections in the Z peak control sample, and the upper left plot in Fig. 6.28 shows the cross-section in this control region as a function of the cut on the missing transverse momentum. The red curve shows the values for Z +jets (based on Alpgen), and the blue curve shows the contributions from other processes, such as $t\bar{t}$ and continuum WW . In the region of interest for the analysis, these sources of contamination are significant.

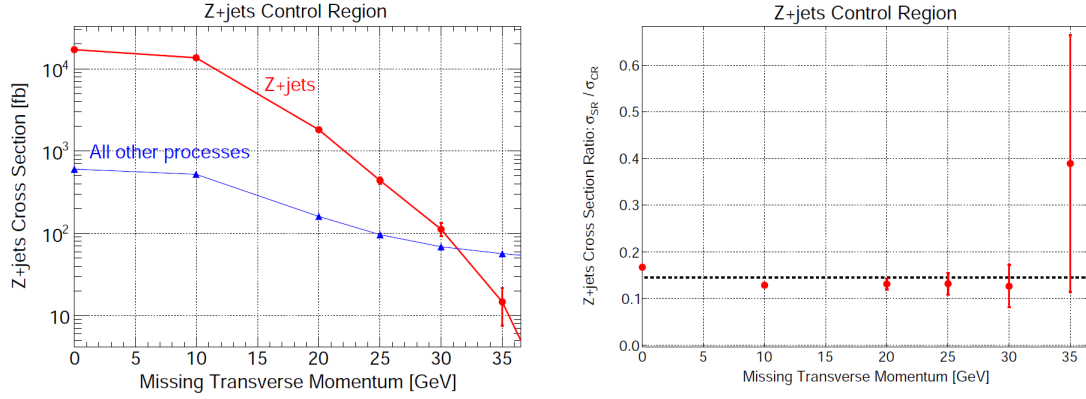


Figure 6.28: Left: the cross-sections for Z +jets and other contaminations in the Z +jets normalisation region as a function of the cut on the missing transverse momentum. The red curve shows the contribution from Z +jets, and the blue curve shows the contribution from all other processes. Right: the ratio of the Z +jets cross-section in the signal region and normalisation region as predicted by Alpgen. Here, the P_T^{miss} cut in the signal region has been loosened to match that in the Z +jets normalisation region.)

In practice, one would like to check missing P_T distribution in the region around the Z peak to make sure that there is not a significant tail, and then obtain an estimate of Z +jets in the signal region by taking the missing P_T performance to be similar in the region with small $m_{\ell\ell}$ and large $m_{\ell\ell}$.

The right plot shows the ratio of the Z +jets cross-sections in the signal region and the normalisation region for various values of the cut on P_T^{miss} . Here, the P_T^{miss} cut in the signal region has been relaxed to match that in the Z +jets normalisation region. If the ratio of cross-sections is fairly at as it is in the case of the MC sample used here (Alpgen), then one can simply read of the P_T^{miss} distribution from the events in the Z peak (after subtracting the contamination from other processes) and use that distribution to estimate the rejection against Z +jets obtained from the P_T^{miss} cut in the signal region.

Since the Z +jets background is a fairly small concern in this analysis, the present study does not pursue a nuanced treatment of the Z +jets background extraction including correction factors for the effects mentioned above and the related systematic errors. The control sample described above is sufficient to demonstrate that the Z +jets background is small enough that its contribution to the signal region can be taken from MC, and that is sufficient for the purposes of the present analysis.

Checks to normalise the $b\bar{b}$ background - $H \rightarrow WW + 1j$

The $b\bar{b}$ background is a potentially dangerous background because of its large cross-section. With the currently available MC samples, it is reduced to a negligible level by the lepton P_T

cuts, the isolation cuts and the missing P_T cut. However, it is possible that this background might give a larger than expected contribution; it is therefore important to have a technique ready to normalise this background in situ.

Following the approach devised for the zero jet analysis (Subsection 6.2.5), the strategy employed here is to select events for which the impact parameter significance of the leptons is large (> 3 for muons, > 6 for electrons) and for which the isolation cut is not applied. As was the case for the zero jet analysis, no MC events survive in the signal region, even if the jet veto cut is removed. Figure 6.29 shows the cross-section in the control region as a function of the jet veto P_T threshold; the lower curve shows the $b\bar{b}$ cross-section alone and the upper curve shows the sum of $b\bar{b}$ and the other processes which contaminate this region (mostly top events). Based on this behaviour, one can check whether the MC describing the $b\bar{b}$ background is correct in its prediction that this contribution is negligibly small.

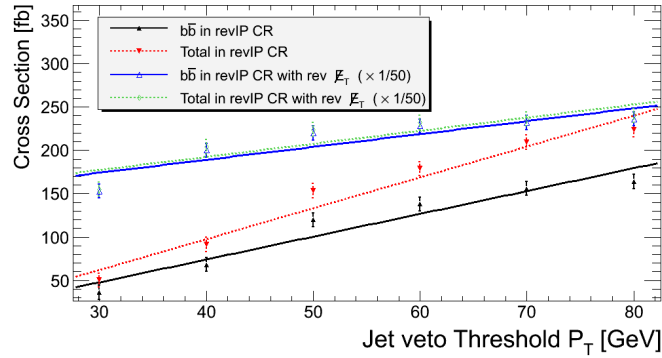


Figure 6.29: Cross-section as function of jet P_T threshold in the $b\bar{b}$ control region and a similar region with an inverted cut on P_T^{miss} .

Table 6.15: Systematic uncertainties for the various extrapolation ratios in the aggressive scenario and the conservative scenario.

Aggressive Scenario					
	α^{WW}	α^{Top}	α^{Wjets}	β^{Top}	β^{Wjets}
Q^2	12.50%	18.53%	0.00%	3.54%	0.00%
Jet Scale Up	2.02%	12.21%	4.31%	7.30%	16.60%
Jet Scale Down	2.01%	16.03%	2.58%	9.49%	4.25%
Jet Resolution	0.00%	0.00%	0.00%	0.00%	0.00%
b -tagging eff.	0.74%	20.94%	0.00%	16.23%	0.00%
MC Statistics	10.54%	20.87%	94.37%	6.29%	48.47%
Total	16.49%	38.40%	94.47%	20.14%	51.24%
Conservative Scenario					
	α^{WW}	α^{Top}	α^{Wjets}	β^{Top}	β^{Wjets}
Q^2	10.45%	34.15%	–	7.19%	–
Jet Scale Up	2.44%	12.12%	–	6.58%	–
Jet Scale Down	5.17%	14.81%	–	8.80%	–
Jet Resolution	0.00%	0.00%	–	0.00%	–
b -tagging eff.	1.59%	28.16%	–	19.39%	–
MC Statistics	13.52%	19.61%	–	6.51%	–
Total	17.92%	50.63%	–	23.40%	–

Results for $H \rightarrow WW + 1j$

As was done for the zero jet analysis, various control samples are incorporated into the sensitivity calculation. The cross-sections and systematic errors are, of course, different; the values for the cross-sections and systematic errors used here are summarised in the previous sections as well as in Appendix A.8.1. The systematic error on the signal is taken to be the sum in quadrature of the jet energy scale uncertainty (6.3%) and the theory uncertainty (2%) as evaluated by varying the factorization and renormalization scales by factors of 4.

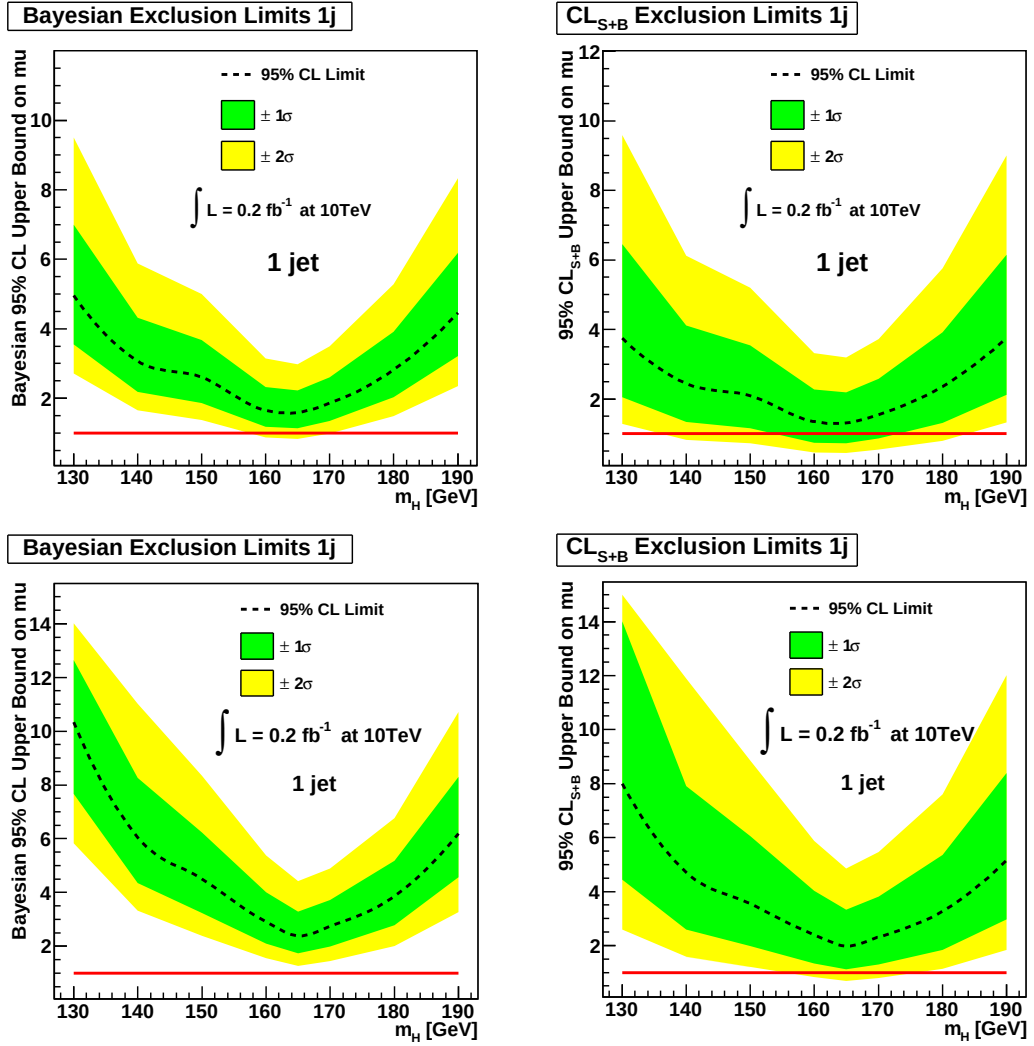


Figure 6.30: Bayesian and Frequentist 95% CL Upper-bound on μ , at $\sqrt{s}=10$ TeV and 200 pb^{-1} of integrated luminosity for aggressive (top) and conservative (bottom) scenarios.

Figure 6.30 shows the expected upper bounds on the Higgs boson signal cross-section (in units of the Standard Model prediction) for the aggressive scenario (top) and the conservative

scenario (bottom), for an integrated luminosity of 200 pb^{-1} at a centre-of-mass energy of 10 TeV. By itself, this channel can come close to excluding Standard Model Higgs boson masses near 160 GeV, but the chances to exclude a significant range are small.

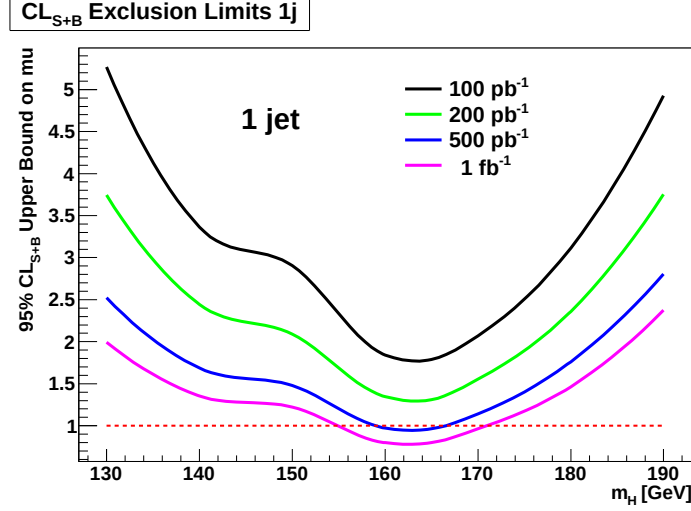


Figure 6.31: Comparisons at different luminosities in the aggressive scenario.

Figure 6.31 shows the expected behaviour of the upper bound for several values of the integrated luminosity, at a centre-of-mass energy of 10 TeV. Approximately 500 pb^{-1} to 1 fb^{-1} of integrated luminosity would be required in order to have a $>50\%$ probability to exclude any part of the Standard Model Higgs boson mass range using the $H + 1j$ channel alone.

PDF Reweighting, sensitivity at 7 TeV - $H \rightarrow WW + 1j$

As it was done in the zero jet, the physics potential for the case of a $\sqrt{s} = 7$ TeV centre-of-mass energy was estimated using an event-by-event PDF re-weighting formalism described in Chapter 4.

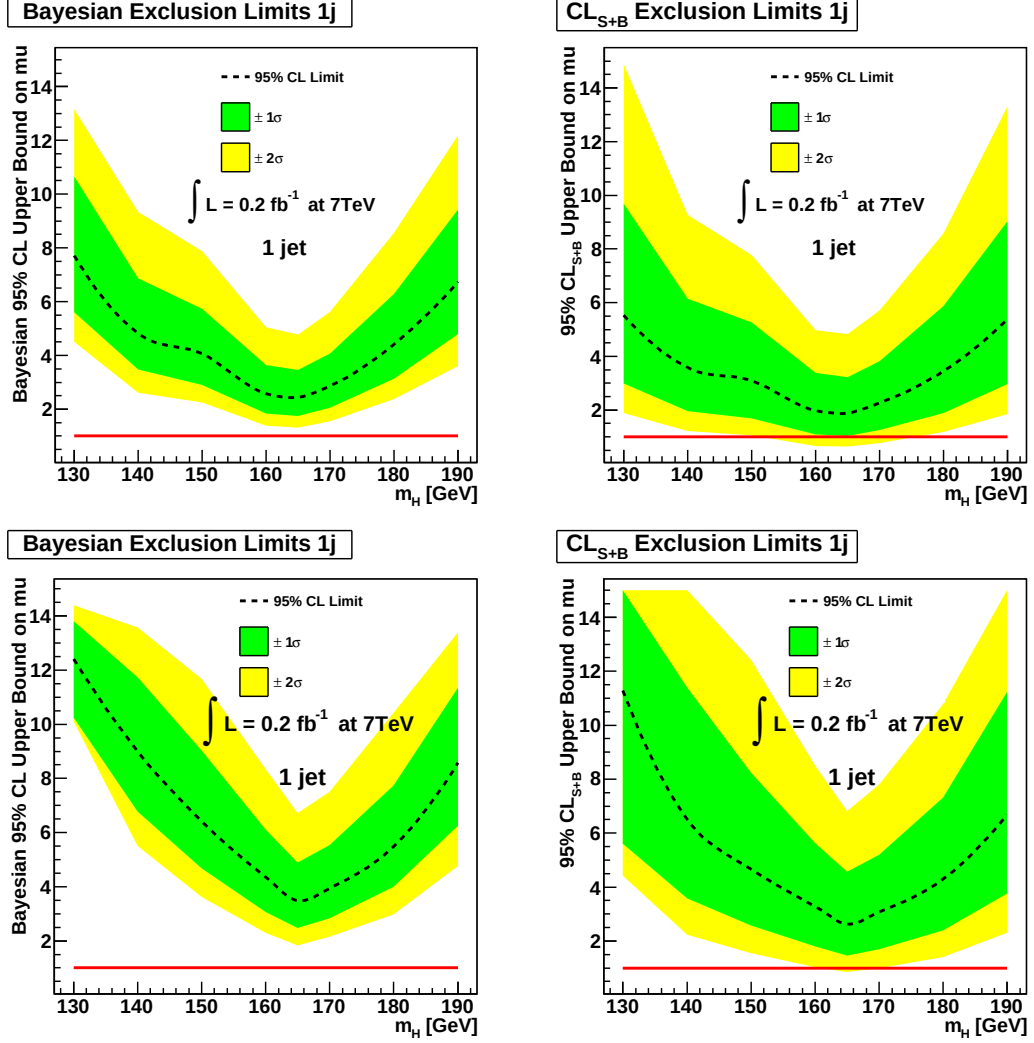


Figure 6.32: Bayesian and Frequentist 95% CL Upper-bound on μ , at $\sqrt{s} = 7$ TeV and 200 pb^{-1} of integrated luminosity for aggressive (top) and conservative (bottom) scenarios.

Figure 6.32 shows the expected upper bound on the Higgs boson production cross-section one would expect after collecting 200 pb^{-1} of integrated luminosity at a centre-of-mass energy of 7 TeV, and Fig. 6.33 shows a comparison between the expected limits for 7 TeV and 10 TeV. The increase in the upper bound that comes from a lowered centre-of-mass energy is less than a factor of two for most values of the Higgs boson mass.

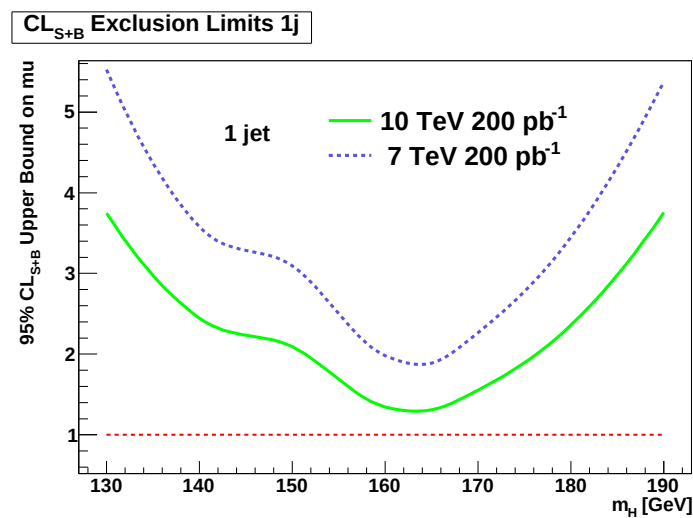


Figure 6.33: Comparisons at different centre-of-mass of energy in the aggressive scenario

6.2.7 2 jet

At the LHC, the Vector Boson Fusion Higgs boson production process has the second largest cross-section in the SM. A Feynman diagram for this process is shown in Fig. 6.34. At $\sqrt{s} = 10$ TeV, for $m_H < 2m_Z$, this process comprises about 10% of the total production cross-section (See Chap 2) and becomes more significant compared to the dominant gluon fusion process as m_H increases. However, this production mode has the advantage that additional event characteristics can be exploited to suppress the large backgrounds. The Higgs boson is accompanied by two jets in the forward regions of the detector, originating from the initial quarks that emit the vector bosons. Higgs boson P_T is relatively higher than in gluon-gluon Fusion due to emitting W/Z . In addition, central jet activity is suppressed due to the lack of colour exchange between the quarks. This is in contrast to most background processes, where there is colour flow in the t -channel. Therefore, in order to enhance the signal-to-background ratio, jet tagging in the forward region of the detector together with a veto of additional jet activity in the central region can be exploited. The search for Higgs bosons in this channel in proton-proton collisions with a centre-of-mass energy of 14 TeV using the ATLAS detector has been already considered in the context of multivariate and fit-based techniques in [27] and using cut-based approach in [136].

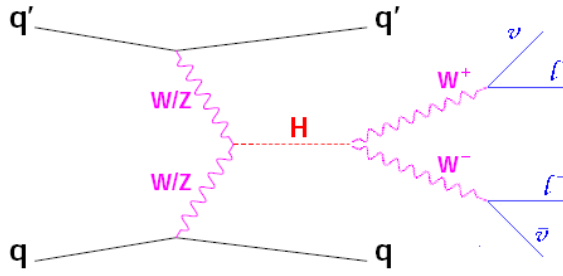


Figure 6.34: Feynman diagram for vector-boson fusion Higgs boson production and its decay into WW pair

Two forward jets from the struck quarks, two isolated leptons, and missing transverse momentum from the two W decays form a distinctive signature for the signal. The distinct kinematics of the jets in VBF events are shown in Fig. 6.35.

Events in with the following criteria are selected:

- Require the presence of least two jets. Based on the scenario considered, jet selections are required to have $P_T > 20$ GeV and $|\eta| < 4.8$ in the aggressive analysis, or $P_T > 30$ GeV and $P_T > 40$ GeV for $|\eta|$ smaller or larger than 3.2. Jets are reconstructed from topological clusters using a cone algorithm with a radius of 0.4. These jets are used for the forward jet tagging later.
- A jet veto helps to suppress backgrounds with heavy jet activity in the central region

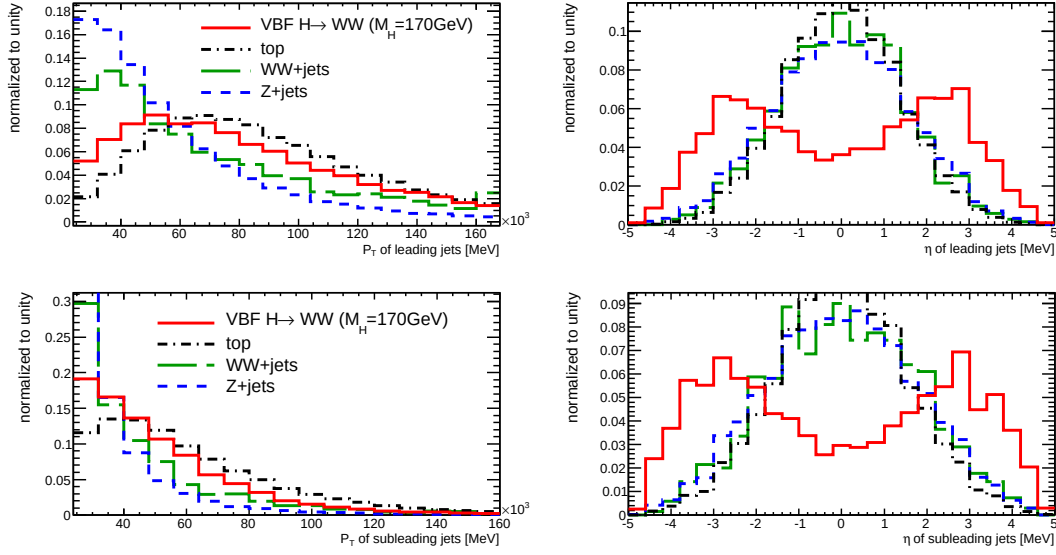


Figure 6.35: Jet kinematics for signal and main backgrounds.

like $t\bar{t}$. Events are rejected if a 3^{rd} jet (apart from the two tagging jets) is found within $|\eta| < 3.2$.

- A b -jet veto is very effective against $t\bar{t}$. An event is ignored if a b -jet is found. A jet is taken to be a b -jet if it has an SV0 b -tagging weight greater than 5.7.
- The two leading jets (the “tag” jets) are required to be in opposite hemispheres: $\eta_{j1} \cdot \eta_{j2} < 0$.
- The P_T of the leading jet must be greater than 40 GeV.
- The forward jets topology is a distinctive characteristic of the Weak Boson Fusion production mechanism and it is extremely effective in rejecting almost all types of backgrounds. The pseudorapidity gap between the tag jets is required to be greater than 3.8. Figure 6.36 shows the distribution of the pseudorapidity between the tag jets for the signal and the main backgrounds.
- The invariant mass m_{jj} of the tag jets can be a selection criterion for the signal process. It is required to be greater than 500 GeV. Figure 6.36 shows the corresponding distributions.
- If no hard initial- or final-state gluons are radiated, it is also expected that the transverse momentum of the Higgs boson will be balanced by the transverse momentum of the two tag jets. The total transverse momentum of two tag leptons, two jets and missing energy is defined as follows:

$$P_T^{tot} = P_T^{l1} + P_T^{l2} + P_T^{j1} + P_T^{j2} + P_T^{miss} \quad (6.10)$$

6.2. $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, design of analysis strategy

Events are required to have $P_T^{tot} < 30$ GeV. Figure 6.36 shows this discriminating variable.

Table 6.16: Effective cross-sections (in fb.) after cuts in the Signal Region, and the corresponding MC uncertainties for the conservative scenario.

flavor channel	signal (fb)	background (fb)					total
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	$di-jets$	
$e\mu$	2.20 ± 0.06	0.26 ± 0.18	0.46 ± 0.22	—	—	—	0.72 ± 0.29
ee	0.73 ± 0.04	—	0.06 ± 0.06	—	—	—	0.06 ± 0.06
$\mu\mu$	1.30 ± 0.05	—	—	—	—	—	—
total	4.23 ± 0.09	0.26 ± 0.18	0.52 ± 0.23	—	—	—	0.78 ± 0.29

Control Samples and Systematics for $H \rightarrow WW + 2j$

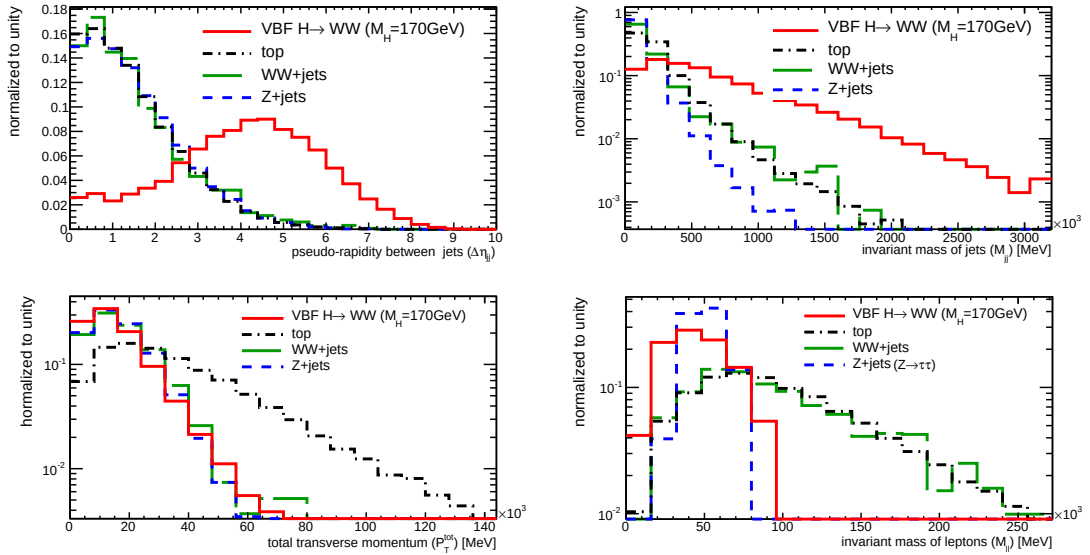


Figure 6.36: Distributions of important discriminating variables for signal and main backgrounds.

It was found that after applying all these selection criteria, none of the available MC events for some important backgrounds remained. Table 6.16 shows the effective cross-sections in the Signal Region for all the relevant processes. Dash indicates lack of statistics in the corresponding MC sample. This is the case for a number of entries in the table; however, it is well known from previous studies that some of these processes are not negligible and therefore should be estimated. In principle, one can use the sum of the cross-sections over the three flavor channels and use that estimate for limits and significance calculation, but in that case the result will be swamped by MC statistical error and even can give an unphysical result. (See, for example, the case of the $\mu\mu$ channel in Table 6.16; the absence of any nonzero background cross-sections is simply due to a statistical fluctuation.)

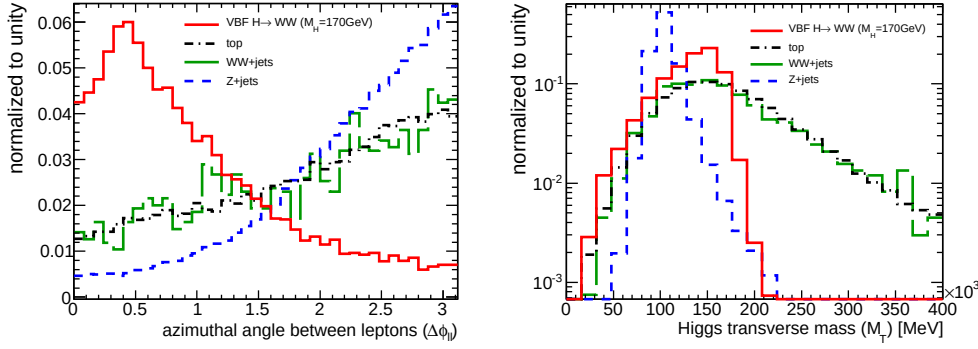


Figure 6.37: Transverse momentum of the missing energy and di-lepton-neutrino system for signal and main backgrounds

Taking into account the lack of statistics in this channel at the beginning of data taking at LHC and some other considerations it was decided to loosen the event selection. On the one hand, removing a cut should be least harmful for the analysis; on the other, one still needs to have decent statistics to be able to make a convincing analysis and not be swamped by unphysical MC fluctuations. After thorough investigation (varying different cuts), an appropriate combination was found. The $\Delta\phi_{ll}$ cut is not very effective in this analysis, especially if it is applied after jet-veto, forward jet tagging and lepton cuts. Following Table A.46 in Appendix A.9.2, it kills 17% of the signal and only 25% of the backgrounds. Therefore this cut can be loosened or turned off completely. Another cut which can be relaxed is the cut on the invariant mass of the tag jets, m_{jj} . This cut is relatively effective (it removes 17% of the signal and 53% of the backgrounds according to the Table A.46), but at the same time this cut makes substantial contribution to the systematic uncertainty (as will be seen in Sec. 6.2.7).

The scenario with loosened $\Delta\phi_{ll}$ and m_{jj} cuts will be referred to as the aggressive scenario, and it is taken as the baseline scenario in this study. Table 6.17 shows the detailed cutflow in the Signal Region for the sum of the three flavor channels in the case of the aggressive scenario. A breakdown into $e\mu$, ee and $\mu\mu$ can be found in Appendix A.9.2.

As can be seen from Table 6.17, the main backgrounds are top and $WW + jets$. The next section describes how to normalise these backgrounds using control samples in the data. The numbers presented in the next subsections are based on the aggressive scenario, corresponding numbers for the conservative scenario can be found in Appendix A.9.2

Normalising top - $H \rightarrow WW + 2j$

Two of the most effective cuts against top background in this analysis are the pseudorapidity gap between tag jets and b -tagging. Therefore it is possible to construct a sample enriched in top by reversing these cuts with respect to the signal region. Signal is removed from the control

6.2. $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, design of analysis strategy

Table 6.17: Cutflow (in fb) signal ($m_H = 170$ GeV) and all relevant backgrounds in the Signal region for the aggressive scenario. Cross-sections in the cutflow table are summed over ee , $e\mu$ and $\mu\mu$ channels. The W +jets column includes contributions from WZ and Wbb , and the Z +jets column includes ZZ and Zbb contributions. The dijets column includes contributions from the $b\bar{b}$ background. The last three rows represent a breakdown of the effective cross-sections after cuts into the three flavor channels, with the corresponding MC statistical uncertainties. Cross-sections are given in fb.

	signal (fb)	background (fb)					
	<i>Signal</i>	WW	$t\bar{t} + Wt$	W +jets	Z +jets	di -jets	<i>total</i>
lepton acceptance	27.45	1220.79	8697.07	1504.30	880895.82	273.04	892591.02
3 rd lepton veto	27.43	1219.88	8646.53	1484.91	880599.62	273.04	892223.98
m_{ll} cuts	25.78	1124.37	7948.08	806.20	121039.00	239.44	131157.08
$p_T^{\text{miss}} > 30/40$ GeV	21.88	703.29	6436.44	410.97	552.36	–	8103.05
$m_T^{\text{ll}\nu} > 30$ GeV	20.78	664.28	5659.01	399.42	224.23	–	6946.95
jet acceptance	15.11	148.05	5057.08	58.31	121.73	–	5385.18
jet-veto	12.94	103.06	2021.62	38.63	63.64	–	2226.94
b -jet veto	12.02	94.55	466.56	35.99	52.05	–	649.15
$\eta_{j1} \cdot \eta_{j2} < 0$	10.64	39.10	197.89	14.15	21.18	–	272.33
$p_T^{\text{lead.jet}} > 40$ GeV	9.61	27.94	165.91	8.38	19.67	–	221.90
$\Delta\eta_{jj} > 3.8$	7.20	4.60	24.15	0.12	3.48	–	32.34
$p_T^{\text{tot}} < 30$ GeV	6.91	3.90	15.74	0.12	3.43	–	23.19
$Z \rightarrow \tau\tau$ rejection	6.76	3.54	14.57	0.12	1.34	–	19.56
$m_{ll} < 80$ GeV	6.59	1.40	3.88	–	1.30	–	6.57
$m_T < m_H$	6.24	1.15	3.41	–	0.12	–	4.68
total	6.24±0.10	1.15±0.39	3.41±0.66	–	0.12±0.12	–	4.68±0.77
$e\mu$	3.21±0.08	0.93±0.36	1.56±0.44	–	0.12±0.12	–	2.61±0.58
ee	1.08±0.04	0.11±0.11	0.34±0.21	–	–	–	0.45±0.23
$\mu\mu$	1.94±0.06	0.11±0.11	1.51±0.45	–	–	–	1.62±0.46

region by reversing the cut on the invariant mass of the leptons: $m_{ll} > 80$ GeV. Table 6.18 shows the detailed cutflow in this control region for the sum over flavor channels and the corresponding effective cross-sections after cuts for the $e\mu$, ee and $\mu\mu$ channels separately. MC statistical uncertainties are also shown. It is valid to say that this control region is dominated by top production.

Normalising WW +jet background - $H \rightarrow WW + 2j$

In order to normalise the WW +jets background, a b -vetoed control region with the same kinematic cuts as in the top control region is used; the only difference between the two regions is that in the b -vetoed control region, the b -tagging cut is reversed. The cutflow for the b -vetoed control region is given in Table 6.19. The ratio between the WW +jets MC cross-sections in the signal region and the WW control region defines the extrapolation factor to normalise the WW +jets background in the signal region from data. But one can see that there is a significant contamination from the top background in the WW control sample; it is important to subtract this contamination. The top control sample defined in the previous subsection can be used, along with the ratio of top cross-sections between the WW control region and

Table 6.18: Cutflow for the top control region summed over ee , $e\mu$ and $\mu\mu$ channels and a breakdown into channels for the final cross-sections (in fb).

	signal (fb)	background (fb)				<i>total</i>
	<i>Signal</i>	<i>WW</i>	$t\bar{t} + Wt$	<i>W + jets</i>	<i>Z + jets</i>	
jet acceptance	15.11	148.05	5057.08	58.31	121.73	5385.18
jet-veto	12.94	103.06	2021.62	38.63	63.64	2226.94
b-jet tagging	0.92	8.51	1555.06	2.64	11.58	1577.79
$\eta_{j1} \cdot \eta_{j2} < 0$	0.79	4.05	678.29	2.37	2.45	687.16
$p_T^{lead,jet} > 40$ GeV	0.77	3.80	632.97	2.37	2.30	641.44
$\Delta\eta_{jj} < 3.8$	0.30	3.44	600.65	1.22	2.11	607.42
$p_T^{tot} < 30$ GeV	0.28	3.33	466.15	1.22	2.02	472.72
$Z \rightarrow \tau\tau$ rejection	0.28	3.21	440.46	1.22	1.69	446.57
$m_{ll} > 80$ GeV	0.01	2.20	233.84	0.12	0.18	236.34
total	0.01±0.004	2.20±0.52	233.84±5.61	0.12±0.12	0.18±0.09	236.34±5.63
$e\mu$	0.01±0.004	1.35±0.41	136.45±4.29	0.12±0.12	0.05±0.05	137.97±4.31
ee	–	0.26±0.18	34.95±2.17	–	0.04±0.04	35.24±2.17
$\mu\mu$	–	0.60±0.27	62.44±2.90	–	0.09±0.06	63.13±2.91

the top control region (β^{Top}) described at the beginning of this section.

Table 6.19: Cutflow for the WW control region summed over ee , $e\mu$ and $\mu\mu$ channels and a breakdown into channels for the final cross-sections (in fb).

	signal (fb)	background (fb)				<i>total</i>
	<i>Signal</i>	<i>WW</i>	$t\bar{t} + Wt$	<i>W + jets</i>	<i>Z + jets</i>	
jet acceptance	15.11	148.05	5057.08	58.31	121.73	5385.18
jet-veto	12.94	103.06	2021.62	38.63	63.64	2226.94
b-jet veto	12.02	94.55	466.56	35.99	52.05	649.15
$\eta_{j1} \cdot \eta_{j2} < 0$	10.64	39.10	197.89	14.15	21.18	272.33
$p_T^{lead,jet} > 40$ GeV	9.61	27.94	165.91	8.38	19.67	221.90
$\Delta\eta_{jj} < 3.8$	2.41	23.35	141.75	8.27	16.19	189.56
$p_T^{tot} < 30$ GeV	2.25	20.35	107.73	7.61	11.97	147.66
$Z \rightarrow \tau\tau$ rejection	2.20	19.51	100.53	7.61	5.64	133.28
$m_{ll} > 80$ GeV	0.07	9.14	57.92	0.38	1.44	68.88
total	0.07±0.01	9.14±1.07	57.92±2.75	0.38±0.22	1.44±0.72	68.88±3.05
$e\mu$	0.06±0.01	5.02±0.80	33.46±2.09	0.26±0.19	0.41±0.41	39.14±2.28
ee	–	0.77±0.31	10.38±1.17	0.12±0.12	0.41±0.41	11.67±1.29
$\mu\mu$	0.01±0.004	3.36±0.65	14.08±1.35	–	0.63±0.44	18.06±1.56

Normalising Z +jets background - $H \rightarrow WW + 2j$

The contribution from Z +jets is negligible in the signal region⁸ according to current MC Samples. But in the WW control region, the Z +jets contribution should be taken into account. With that in mind, a special control region can be constructed which is mainly based on the WW control region where two cuts are modified: the invariant mass of tag leptons is required to be inside the Z -peak, i.e. $|m_{ll} - m_Z| < 10$ GeV, and the missing transverse momentum

⁸According to Table 6.17; there is one event from $Z \rightarrow \tau\tau$ in $e\mu$ channel which survived all the cuts, but the corresponding cross-section is small in comparison with signal and other backgrounds and therefore it was neglected.

6.2. $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, design of analysis strategy

should be less than 40 GeV. The rest of the cuts are the same as in the WW control region. This control region can be used to estimate the Z contribution in ee and $\mu\mu$ channels only because it is based on the Z -peak; the Z contribution in $e\mu$ channel should be heavily suppressed by $Z \rightarrow \tau\tau$ rejection. Table 6.20 contains the cut-flow for that control region and final cross-sections after cuts. As expected, this is a pure Z +jets region.

Table 6.20: Cutflow for the Z control region summed over ee , $e\mu$ and $\mu\mu$ channels and a breakdown into channels for the final cross-sections (in fb).

	signal (fb)	background (fb)				
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	<i>total</i>
$ m_{ll} - m_Z < 10$ GeV	1.45	170.52	1238.81	710.49	756029.19	758174.22
$p_T^{\text{miss}} < 40$ GeV	0.40	75.27	231.24	543.01	755400.85	756275.57
$m_T^{ll\nu} > 30$ GeV	0.08	25.51	78.22	220.26	633412.12	633752.91
jet acceptance	0.05	2.26	26.94	85.45	26774.56	26889.21
b-veto (SV0)	0.05	2.13	5.48	78.70	24950.58	25036.88
$\eta_{j1} \cdot \eta_{j2} < 0$	0.04	0.86	2.25	15.30	9965.83	9984.25
$p_T^{\text{lead.jet}} > 40$ GeV	0.04	0.73	2.39	11.58	4887.01	4901.71
$\Delta\eta_{jj} > 3.8$	0.01	0.73	2.39	10.18	4229.22	4242.53
$p_T^{\text{tot}} < 30$ GeV	0.01	0.62	2.19	8.14	3816.82	3827.77
$Z \rightarrow \tau\tau$ rejection	–	0.25	1.85	2.33	1417.13	1421.56
$\Delta\phi_{ll} < 1.6$	–	0.25	1.85	2.33	1417.13	1421.56
total	–	0.25±0.18	1.85±0.49	2.33±0.57	1417.13±34.28	1421.56±34.29
$e\mu$	–	–	0.76±0.32	–	0.05±0.05	0.81±0.32
ee	–	–	0.48±0.25	0.56±0.28	539.08±22.34	540.12±22.34
$\mu\mu$	–	0.25±0.18	0.62±0.28	1.76±0.49	878.00±26.00	880.63±26.01

Systematic uncertainties

Similarly to the zero and one jet cases, for each of the control regions a ratio is used to measure the respective background event yields. There are five⁹ scale factors in this analysis which are used to normalise backgrounds.

The deviation of the extrapolation ratios for a given scale from the central value is calculated and the largest one is taken as a Q^2 scale uncertainty. Table 6.21 collects the result of the analysis of the Q^2 -varied samples. MC statistical uncertainties are shown both for ratios and their deviation. Taking the largest deviation one can estimate the Q^2 scale uncertainty: $\Delta\alpha_{Q^2}^{\text{Top}} \approx 10\%$, $\Delta\beta_{Q^2}^{\text{Top}} \approx 5\%$ and $\Delta\alpha_{Q^2}^{\text{WW}} \approx 35\%$.

It is expected that alteration of the Q^2 scale should mostly affect the jet activity in the event and, consequently, ratios of cross-section between regions where jet-related cuts are different. At first glance, the values in Table 6.22 seem to suggest that in the case of the aggressive scenario (where the m_{jj} cut is not applied in either the signal region or the top control region) the Q^2 scale uncertainty on α^{Top} is almost 4 times smaller than in the conservative case (where m_{jj} is reversed). However, it is worth noting that this is possibly an artifact of the limited size of the

⁹Because of the lack of statistics in the Z MC Samples, this contribution was taken from MC and therefore systematic checks have not been performed on the Z scale factors ($\alpha^{Z,jets}$ and $\beta^{Z,jets}$)

Table 6.21: Extrapolation ratios and their deviations from the central value for top and WW backgrounds, in the aggressive scenario.

	central value	scale 1	scale 2	scale 3	scale 4
α^{Top}					
$e\mu$ channel deviation (%)	0.0173 ± 0.0015 –	0.0214 ± 0.0026 24 ± 11	0.0157 ± 0.0015 9 ± 12	0.0158 ± 0.0016 9 ± 12	0.0191 ± 0.0017 10 ± 11
ee channel deviation (%)	0.0240 ± 0.0028 –	0.0204 ± 0.0040 15 ± 19	0.0200 ± 0.0035 16 ± 17	0.0284 ± 0.0043 19 ± 16	0.0264 ± 0.0046 10 ± 19
$\mu\mu$ channel deviation (%)	0.0237 ± 0.0024 –	0.0214 ± 0.0040 10 ± 19	0.0247 ± 0.0027 4 ± 14	0.0238 ± 0.0032 0 ± 16	0.0199 ± 0.0027 16 ± 14
total deviation (%)	0.0201 ± 0.0011 –	0.0213 ± 0.0019 6 ± 10	0.0188 ± 0.0013 7 ± 8	0.0198 ± 0.0014 1 ± 9	0.0203 ± 0.0014 1 ± 9
β^{Top}					
$e\mu$ channel deviation (%)	0.2223 ± 0.0056 –	0.2152 ± 0.0084 3 ± 4	0.2261 ± 0.0060 2 ± 4	0.2149 ± 0.0066 3 ± 4	0.2245 ± 0.0067 1 ± 4
ee channel deviation (%)	0.2236 ± 0.0090 –	0.2401 ± 0.0161 7 ± 7	0.2097 ± 0.0109 6 ± 6	0.2258 ± 0.0130 1 ± 7	0.2395 ± 0.0134 7 ± 6
$\mu\mu$ channel deviation (%)	0.2091 ± 0.0078 –	0.2403 ± 0.0129 15 ± 6	0.2290 ± 0.0086 10 ± 5	0.2035 ± 0.0089 3 ± 6	0.2277 ± 0.0096 9 ± 5
total deviation (%)	0.2189 ± 0.0041 –	0.2258 ± 0.0065 3 ± 3	0.2244 ± 0.0045 3 ± 3	0.2135 ± 0.0049 2 ± 3	0.2275 ± 0.0051 4 ± 3
α^{WW}					
$e\mu$ channel deviation (%)	0.1972 ± 0.0112 –	0.2622 ± 0.0133 33 ± 5	0.1909 ± 0.0154 3 ± 10	0.2293 ± 0.0152 16 ± 7	0.1632 ± 0.0093 17 ± 7
ee channel deviation (%)	0.2889 ± 0.0293 –	0.3667 ± 0.0314 27 ± 10	0.2568 ± 0.0371 11 ± 16	0.3210 ± 0.0374 11 ± 14	0.2118 ± 0.0212 27 ± 10
$\mu\mu$ channel deviation (%)	0.2823 ± 0.0213 –	0.3648 ± 0.0236 29 ± 7	0.2870 ± 0.0293 2 ± 12	0.2917 ± 0.0264 3 ± 11	0.2385 ± 0.0180 15 ± 9
total deviation (%)	0.2315 ± 0.0095 –	0.3056 ± 0.0111 32 ± 4	0.2255 ± 0.0130 3 ± 7	0.2593 ± 0.0126 12 ± 6	0.1900 ± 0.0078 18 ± 5

MC samples used to evaluate this uncertainty. The same effect is present, although somewhat less pronounced, for the other ratios as well.

Table 6.22: Comparison of Q^2 scale uncertainty on extrapolation ratios between conservative and aggressive scenarios.

scenario	$\Delta\alpha_{syst}^{Top}$	$\Delta\beta_{syst}^{Top}$	$\Delta\alpha_{syst}^{WW}$
conservative	38%	8%	45%
aggressive	10%	5%	35%

Table 6.23 summarises systematic uncertainties obtained when the different variations described on the Subsection 6.2.5 are applied.

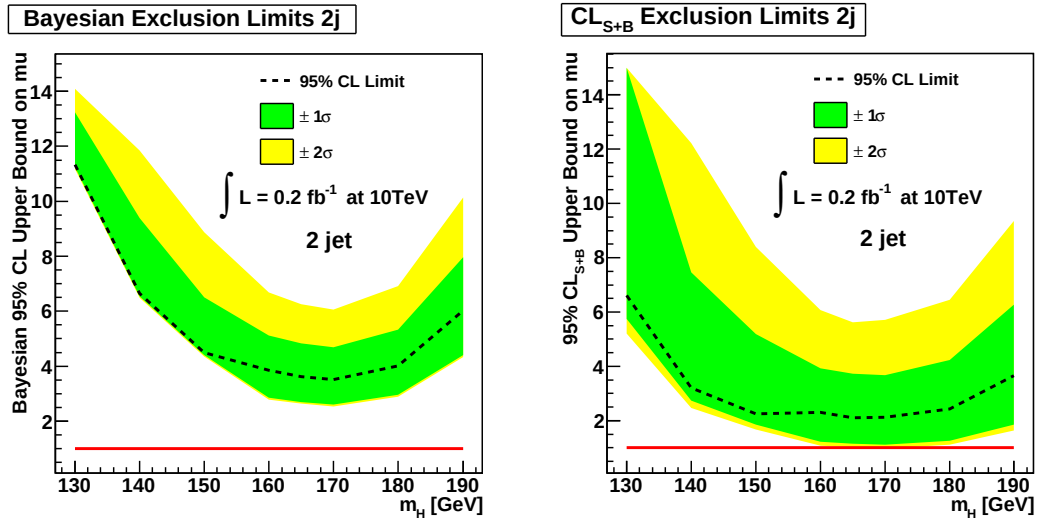
Results for $H \rightarrow WW + 2j$

As done in the zero and one jet analyses, statistical methods employed for the exclusion limits calculations are based on the Frequentist profile likelihood ratio and Bayesian formalisms.

Table 6.23: Systematic uncertainties on extrapolation ratios based on fast simulation. Aggressive scenario.

uncertainty	$\Delta\alpha_{syst}^{Top}$	$\Delta\beta_{syst}^{Top}$	$\Delta\alpha_{syst}^{WW}$
Q^2 scale	10%	5%	35%
jet energy scale (up)	8.51%	0.07%	13.34%
jet energy scale (down)	0.91%	1.04%	16.52%
jet energy resolution	1.04%	0.10%	2.99%
b-tagging efficiency	19.90%	37.98%	0.57%
light jet rejection	1.00%	0.95%	0.60%

Figures 6.38, 6.39, 6.40 show the expected upper bound on the Standard Model Higgs boson cross-section divided by the Standard Model prediction at 10 TeV for the combination of the $e\mu$, ee and $\mu\mu$ channels using Bayesian and Frequentist approaches for integrated luminosity of 200 pb^{-1} , 500 pb^{-1} , 1 fb^{-1} correspondingly. The cross-sections and systematic uncertainties defined in the previous sections for the aggressive scenario were used to obtain these limits.


 Figure 6.38: Upper bound on the Standard Model Higgs boson cross-section with 200 pb^{-1} at 10 TeV. Bayesian and Frequentist approaches. For the aggressive scenario.

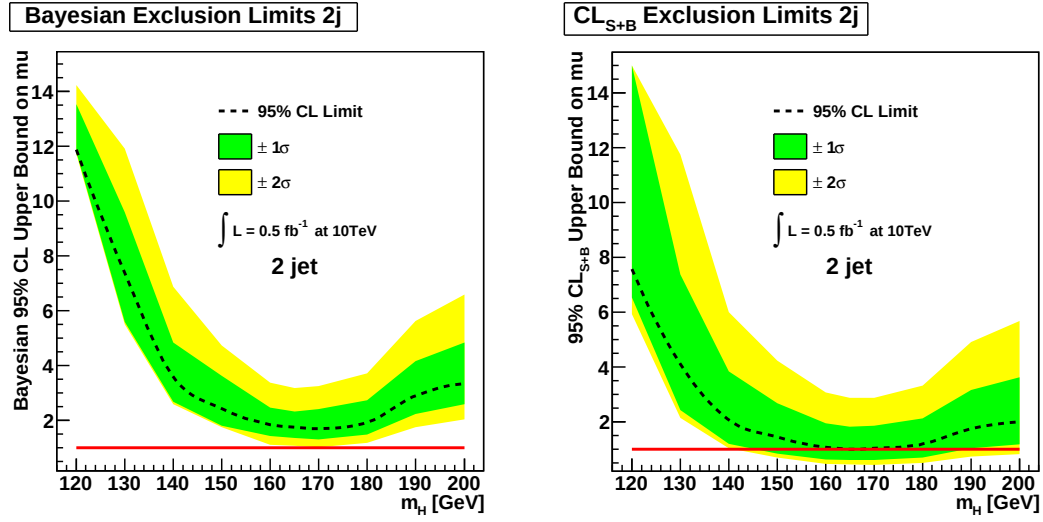


Figure 6.39: Upper bound on the Standard Model Higgs boson cross-section with 500 pb^{-1} at 10 TeV. Bayesian and Frequentist approaches. For the aggressive scenario.

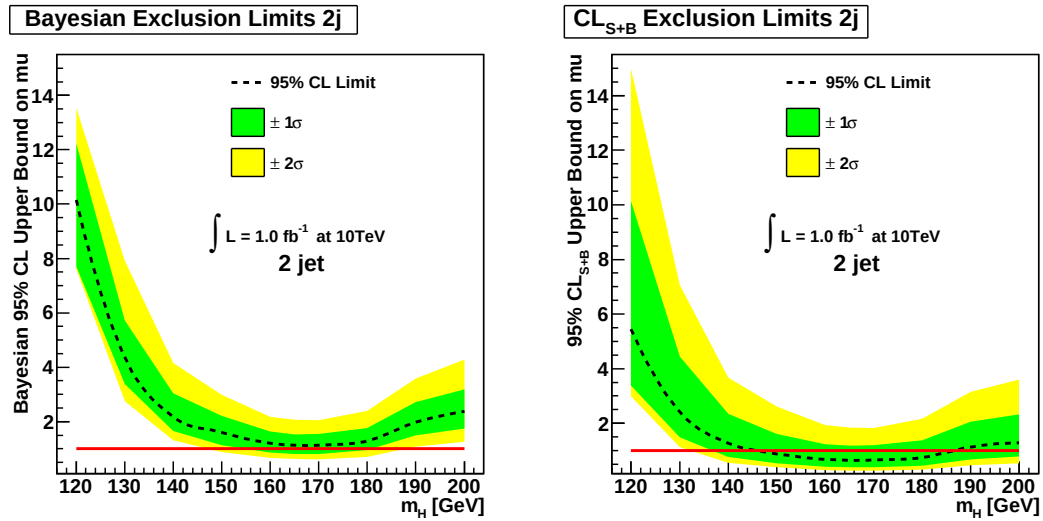


Figure 6.40: Upper bound on the Standard Model Higgs boson cross-section with 1 fb^{-1} at 10 TeV. Bayesian and Frequentist approaches. For the aggressive scenario.

PDF Reweighting, sensitivity at 7 TeV - $H \rightarrow WW + 2j$

As done for the zero and one jet analyses, it was possible to use the available 10 TeV MC samples to estimate the results one would expect at lower centre-of-mass energies. The parton distribution function reweighting technique is described in details in Chap. 4. Exclusion limits are shown in Figures, 6.41, 6.42. Results at 7 TeV for the conservative scenario are presented in Appendix A.9.4.

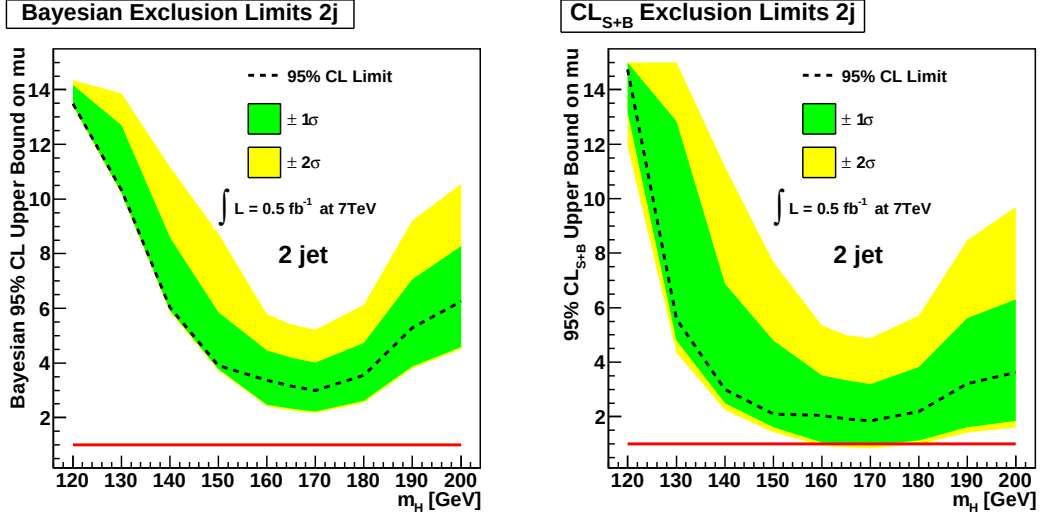


Figure 6.41: Upper bound on the Standard Model Higgs boson cross-section with 500 pb^{-1} at 7 TeV. Bayesian and Frequentist approaches. For the aggressive scenario.

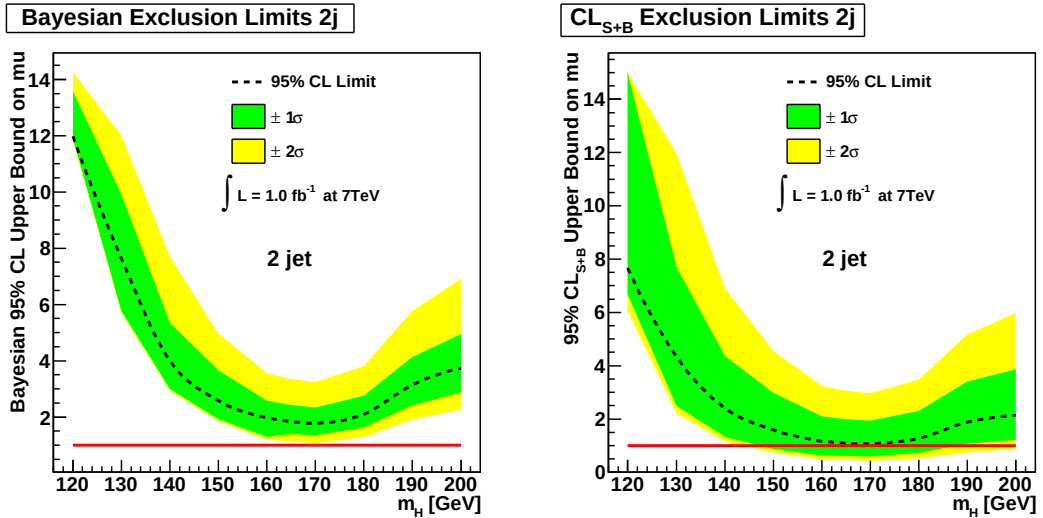


Figure 6.42: Upper bound on the Standard Model Higgs boson cross-section with 1 fb^{-1} at 7 TeV. Bayesian and Frequentist approaches. For the aggressive scenario.

scenario	integrated luminosity (fb ⁻¹)		
	0.2	0.5	1.0
10 TeV			
aggressive	$\mu > 2$	165-175	145-185
conservative	$\mu > 3$	$\mu > 1.5$	$\mu > 1$
7 TeV			
aggressive	$\mu > 3$	$\mu > 2$	$\mu > 1$
conservative	–	$\mu > 2$	$\mu > 1.5$

Table 6.24: Exclusion limits for Standard Model weak boson fusion Higgs boson at 10 and 7 TeV for aggressive and conservative scenarios with different integrated luminosities.

Estimation of exclusion limits of the Standard Model Higgs boson via the VBF mechanism has been performed in the mass range from 120 to 200 GeV. This production mode is characterised by two high- P_T jets in the forward region of the detector what gives a very good suppression power against all the relevant backgrounds. Nevertheless there are several backgrounds which has to be normalised from data: top production, WW +jets and Z +jets¹⁰. Corresponding control regions have been defined in order to estimate these backgrounds. Extrapolation ratios from the control regions to the signal region have been derived from MC and systematic uncertainties on these ratios has been estimated. A number of sources of the systematics have been considered: Q^2 scale, jet energy and resolution, missing transverse momentum, b-tagging and light-jet rejection uncertainties.

In order to cope with limited statistics (especially with the very first data) some of the cuts have been loosened. That led to better statistical evidence and smaller systematic uncertainty than in the conservative case where all the cuts are applied. Moreover, to model limited performance of the ATLAS detector at the very beginning of data-taking, another scenario has been proposed- conservative case includes tightening P_T threshold for jets and missing transverse momentum. This scenario has been evaluated for the same centre-of-mass energy and luminosity conditions as in the aggressive scenario.

Sensitivities at 10 TeV with 200, 500, and 1000 pb⁻¹ of data have been evaluated for both scenarios. Re-weighted 10 TeV samples have been used to study 7 TeV centre-of-mass energy regime, corresponding sensitivity has been checked as well. Table 6.24 collects corresponding upper limits on μ in the case when μ is larger than 1 and excluded mass range when it is smaller than 1. Only limits based on CL_{S+B} method is shown as it has better sensitivity. At 10 TeV one can expect to exclude SM weak boson fusion Higgs boson in the mass range from 165 to 175 GeV with 0.5 fb⁻¹ of data, and in the mass range from 145 to 185 GeV with 1 fb⁻¹ of data, if cuts corresponding to aggressive scenario are applied. At lower luminosity at 10 TeV and at 7 TeV and in the case of conservative scenario it is possible to set limits on $\mu > 1$.

¹⁰ Z +jets background is negligible with the existent MC samples, though the corresponding control region has been constructed

6.2.8 Combination of $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ channels - 7 TeV

As in the sections summarising the individual channels, results were presented using both Bayesian and Frequentist techniques. In both cases, the formalisms used for the significance calculation in the individual channels are described in Sec. 6.2.4 and Appendix A.3. However, it is necessary to specify a few additional details relevant to the combination calculation:

- Only one signal normalisation parameter is used for all three channels. As the integrated luminosity becomes large, it would make sense to introduce a separate normalisation parameter for the $H + 2j$ channel, since the signal production in this channel proceeds via a different mechanism which is sensitive to different couplings than the $H + 0j$ and $H + 1j$ channels. However, such a possibility is not studied here.
- The present combination assumes no correlated systematics on background normalisations in different jet multiplicity bins. In the sensitivity calculations presented in the studies of the individual channels, for example, the ratios of background cross-sections in the same-flavor and opposite flavor channels were fixed, i.e. the significance calculation assumed that the relative efficiency of the electron and muon reconstruction was well-known. It is tempting to do something similar here and introduce, for example, a global normalisation parameter for the top background which influences the top background estimates in all three jet multiplicity bins. Such an approach would most likely decrease the statistical error on the determination of the top background normalisation because the normalisation parameter would be constrained by observations in all three top control samples. However, it is not obvious that the relevant systematic uncertainties would automatically be taken into account in that sort of approach. The present study therefore treats the background estimates in the different jet multiplicity bins separately.
- The systematic error on the signal efficiency is a matter which, in principle, needs to be treated with some care, since a correlation in the systematic uncertainty on the signal would propagate much more directly into the limits obtained on the cross-section than a correlation in the systematic error on the background normalisations. The analyses of the individual channels used in this combination have all included studies of the uncertainty in the signal efficiency arising from lepton reconstruction efficiency, jet energy scale and resolution, and, in the case of $H + 0j$ and $H + 1j$, theoretical uncertainty arising from altered Q^2 scales. The uncertainty arising from lepton reconstruction efficiency is small in the case of single channels, but clearly this is strongly correlated in different jet multiplicity bins. A strongly correlated uncertainty can weaken the expected limit. The uncertainty arising from lepton reconstruction efficiency is therefore taken to be exactly correlated across all three jet multiplicity bins. The jet energy scale and theory uncertainties are another matter; events can “migrate” from one jet multiplicity bin to another. This suggests an anticorrelation, which would yield a stronger limit if it were included in the calculation. However, any such anticorrelation is ignored in the

present analysis. The uncertainties arising from jet energy scale, resolution, and theory systematics are taken to be completely uncorrelated.

As was done for each of the individual channels, the upper limit is computed in terms of a scale factor $\mu = \sigma/\sigma_{SM}$, so that $\mu=1$ corresponds to the SM prediction of the Higgs boson cross-section, and the performance of the calculation is studied with toy MC. For the final results presented in the plots, the expected upper bounds on the signal are converted to absolute cross-sections by multiplying by the predicted cross-section in the SM.

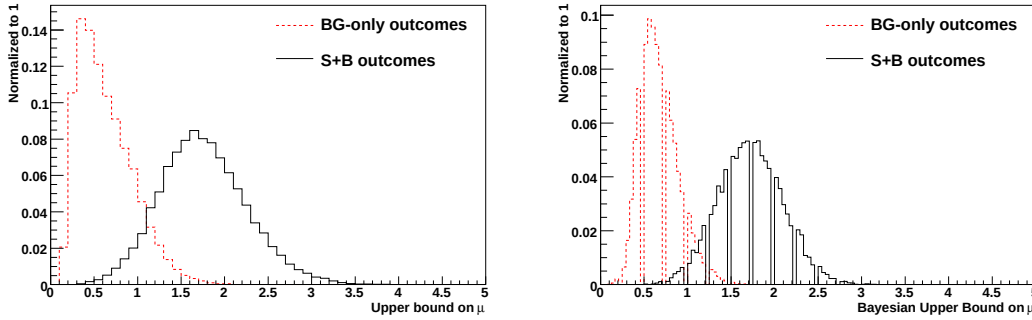


Figure 6.43: A check on the coverage of the expected upper limit on the cross-section for a representative Higgs boson mass of 160 GeV. The red histograms show the distributions for background-only outcomes; the black histograms show the distributions for signal-plus-background outcomes. Left: the distributions for the upper limits using the Frequentist Likelihood Ratio treatment, with an integrated luminosity of 1 fb^{-1} . Right: the corresponding distributions obtained using the Bayesian procedure. The empty bins in the distributions are a consequence of an artificial discreteness of the Bayesian upper limits which results from the fact that the posterior distribution is approximated using a histogram.

To test the upper limits obtained, the performance is checked directly by numerically computing the probability that a signal excess that is really present in the data is incorrectly excluded. That is, for a given Higgs boson mass and integrated luminosity, the observed upper limit is calculated for each outcome in a sample of toy MC outcomes which include both signal and background, and the fraction of outcomes where the upper limit on the signal rate is less than the true signal rate is computed. The upper bounds that are set on the cross-section in the present study are 95% CL limits, so this probability should ideally be close to, but preferably not more than, 5%. Figure 6.43 shows an example for a representative Higgs boson mass of 160 GeV and an integrated luminosity of 1 fb^{-1} . The area underneath the black curves and below $\mu = 1$ gives the probability to falsely exclude the signal for that value of the Higgs boson mass and integrated luminosity. Figure 6.44 shows the value of this probability as a function of the Higgs boson mass, for both the Bayesian and Frequentist upper limits for several values of the integrated luminosity. For lower luminosities, the probability to falsely exclude a signal using the Frequentist method when a signal is actually present can be as large as about 7%.

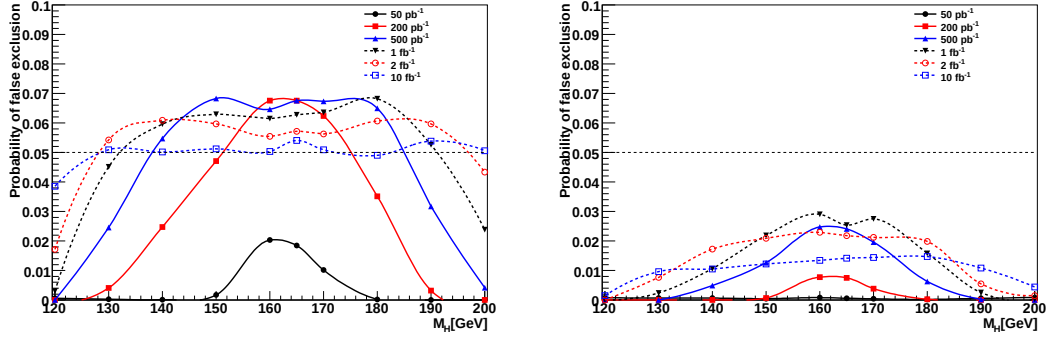


Figure 6.44: A check on the coverage of the expected upper limit on the cross-section for a representative Higgs boson mass of 160 GeV. Left: the probability to incorrectly exclude a SM signal using the Frequentist limit, when such a signal is actually present. Right: same as Left, but using the Bayesian limit.

This is not ideal for a 95% confidence level limit, but it is a consequence of using the χ^2 approximation in a regime where luminosities are too low for this approximation to be really valid. It is expected that a numerical computation of p -values would yield better coverage. As the luminosity increases, the probability of false discovery using the Frequentist method approaches 5%, as expected. Apart from this feature at low luminosity, the probability to falsely exclude the signal when it is present is generally in the acceptable range, so the limits reported in the next section are said to have good coverage. The expected upper limit is the median of the red histogram, and estimates of the expected $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations are taken from the red histogram as well.

Results and Conclusions

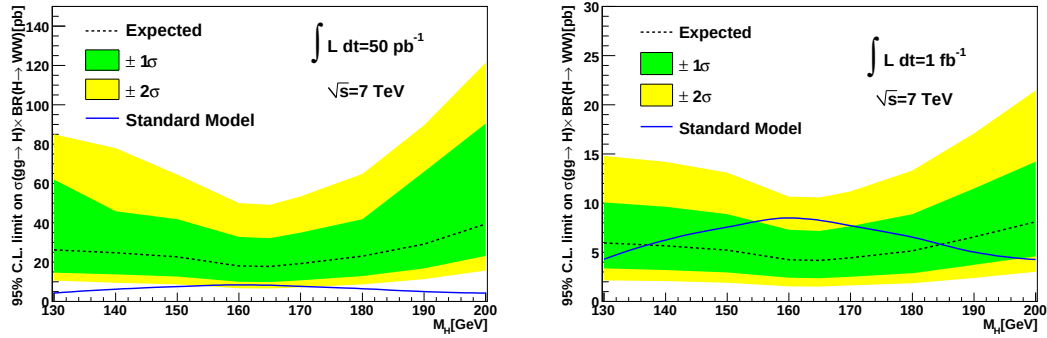


Figure 6.45: The expected Frequentist upper bound on the Higgs boson production cross-section as a function of its mass, after 50 pb⁻¹ (Left) and 1 fb⁻¹ (Right) of integrated luminosity are collected. Here, results are shown for the aggressive selections.

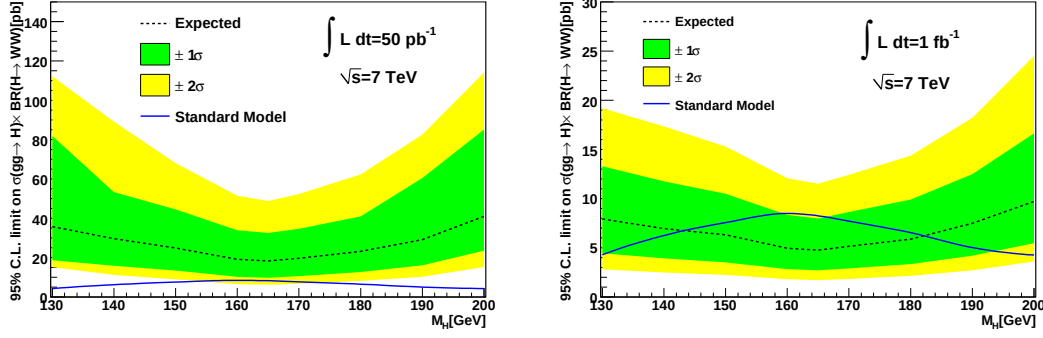


Figure 6.46: The expected Frequentist upper bound on the Higgs boson production cross-section as a function of its mass, after 50 pb^{-1} (Left) and 1 fb^{-1} (Right) of integrated luminosity are collected. Here, results are shown for the conservative selections.

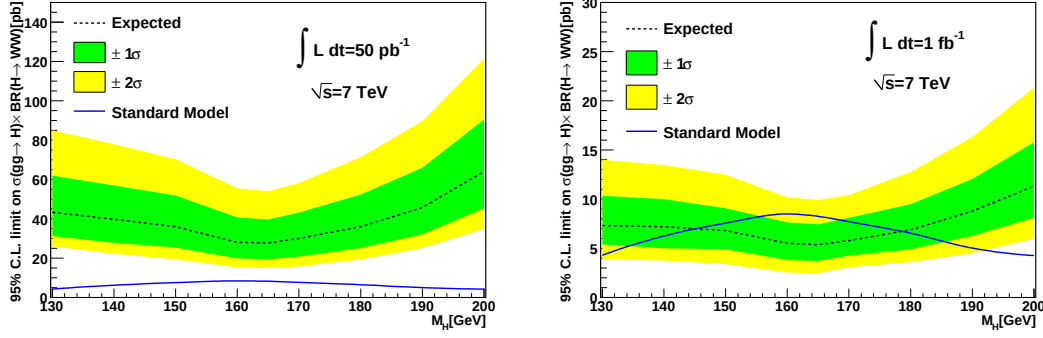


Figure 6.47: The expected Bayesian upper bound on the Higgs boson production cross-section as a function of its mass, after 50 pb^{-1} (Left) and 1 fb^{-1} (Right) of integrated luminosity are collected. Here, results are shown for the aggressive selections.

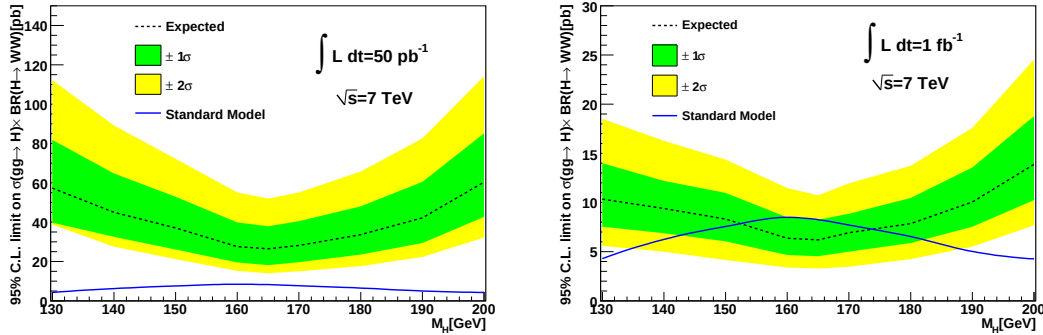


Figure 6.48: The expected Bayesian upper bound on the Higgs boson production cross-section as a function of its mass, after 50 pb^{-1} (Left) and 1 fb^{-1} (Right) of integrated luminosity are collected. Here, results are shown for the conservative selections.

Figures 6.45 and 6.46 show the Frequentist limits, including their expected statistical fluctuations, as functions of the Higgs boson mass for integrated luminosities of 50 pb^{-1} and 1 fb^{-1} and using the aggressive and conservative selections, respectively. Figures 6.47 and 6.48 show the corresponding results using the Bayesian formalism. Figures 6.49 and 6.50 show the evolution of the expected limits obtained using both formalisms as the total integrated luminosity increases. Table 6.25 shows the Frequentist results in a tabular format. Using the conservative selection, the SM Higgs boson is expected to be excluded for m_H between approximately 145 GeV and 180 GeV with 1 fb^{-1} of integrated luminosity. However, the possible statistical fluctuations on this statement are large; if the observed measurement lies within the green $\pm 1\sigma$ band in the plot, it is possible that no region of m_H will actually be excluded or that the range from about 135 GeV to 190 GeV will be excluded.

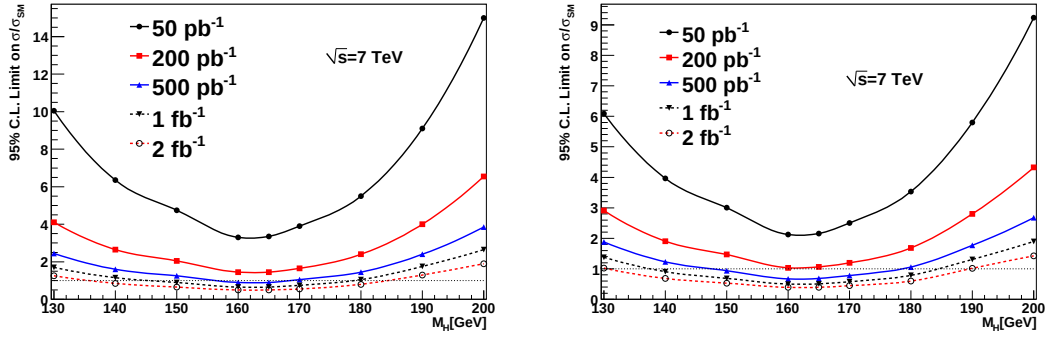


Figure 6.49: The median expected limits obtained using the Bayesian (Left) and Frequentist (Right) formalisms, for the aggressive selections, after collecting various amounts of integrated luminosity.

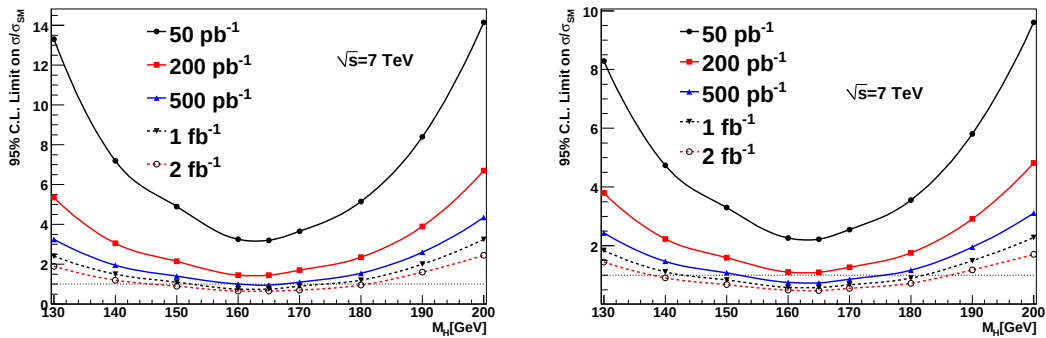


Figure 6.50: The median expected limits obtained using the Bayesian (Left) and Frequentist (Right) formalisms, for the conservative selections, after collecting various amounts of integrated luminosity.

Table 6.25: The upper bounds on the Higgs boson production cross-section (in units of the SM cross-section) as a function of mass and for several integrated luminosities. Here, results are shown for the Frequentist limit-setting procedure.

Aggressive Selection					
Mass[GeV]	50 pb ⁻¹	200 pb ⁻¹	500 pb ⁻¹	1 fb ⁻¹	2 fb ⁻¹
130	6.09	2.91	1.88	1.38	1.02
140	3.96	1.90	1.23	0.91	0.68
150	3.00	1.47	0.94	0.69	0.53
160	2.12	1.03	0.67	0.50	0.39
165	2.16	1.06	0.68	0.51	0.39
170	2.50	1.19	0.78	0.58	0.45
180	3.53	1.68	1.06	0.79	0.60
190	5.80	2.80	1.77	1.31	1.02
200	9.23	4.32	2.67	1.90	1.43
Conservative Selection					
130	8.29	3.80	2.44	1.84	1.44
140	4.74	2.23	1.47	1.11	0.91
150	3.30	1.60	1.08	0.84	0.68
160	2.26	1.10	0.75	0.58	0.49
165	2.22	1.09	0.74	0.58	0.47
170	2.55	1.27	0.86	0.67	0.55
180	3.55	1.76	1.17	0.90	0.72
190	5.81	2.91	1.95	1.49	1.18
200	9.61	4.82	3.11	2.28	1.71

Conclusions

The search of the SM Higgs boson decaying into a pair of weak bosons with the corresponding leptonic decay of the W or Z has been studied.

The MC studies that helped to design the analysis strategies for the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ and $H \rightarrow Z Z^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ decay modes are described. The cutbased analyses currently used by the ATLAS collaboration on both of these channels, are largely based on the studies and optimisations presented on this work.

Contributions to the development of a Tier3-prototype as well as preliminary studies of muon reconstruction resolutions on $Z \rightarrow \mu\mu$ events with the early LHC data are equally presented.

In the $H \rightarrow Z Z \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay channel, $\int \mathcal{L} dt = 4.7 \text{ fb}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ data taken by the ATLAS detector during 2011 were analysed. The data is compared to the background predictions and 95% CL upper limits on the Higgs boson production cross section in a mass range between 200 and 900 GeV are presented. With this channel, the SM Higgs boson is excluded at 95% CL in the mass range between 319 and 558 GeV. A summary of ATLAS SH Higgs boson searches is also presented. With the statistical combination of these results, the Higgs boson existence is constrained to be in a narrow window between 122.5 GeV and 129 GeV with 95% confidence level; where an excess of 2.6σ local significance is observed. More data is needed to either strength the observed excess, or to ruled out in the case it is a statistical fluctuation.

At the beginning of March 2012, the LHC restarted its collision program. After the incredibly smooth performance during 2010 and 2011, the accelerator team has gained enough confidence with the machine to increase the centre-of-mass energy to 8 TeV. The instantaneous luminosities are already at the designed edge. Events with an average of 30 interactions per bunch crossing are being taken. This presents new challenges for the physics analysis. Nevertheless with expectations of integrated luminosities rounding the $\int \mathcal{L} dt = 5 \text{ fb}^{-1}$ of 8 TeV data by summer 2012, could mean a milestone moment for the Higgs boson search. Analyses are in constant improvements. A better understanding of the detector allows to probe multivariate techniques to better reconstruct objects and to discriminate signal and backgrounds. Larger event statistics can be used to perform multidimensional fits that would help to constraint and reduce uncertainties on the different searches. Some channels with weaker sensitivity

have been started to be used, those including τ leptons or rare decays like the $H \rightarrow Z\gamma$, which can be potentially used to measure Higgs boson properties.

With the discovery of the Higgs boson the “new”-physics program in the LHC experiments would just start. A low mass Higgs boson is the best scenario for SUSY models. And for the Higgs boson physics itself a large number of measurements would then be required: mass, width, cross-section, spin, couplings, branching fractions, . . . , a many others. They shall tell the actual details and nature of the Higgs mechanism.

A Appendix

A.1 Muon spectrometer alignment check

This appendix gathers further information on the $Z \rightarrow \mu\mu$ resolution studies with early data. They use about 3000 $Z \rightarrow \mu\mu$ event candidates. Both of the ATLAS muon reconstruction algorithms, STACO and MuID, are compared. Resolution and best fitted mass peak values for various binning of the data are shown. It includes η (barrel-endcap configurations), ϕ , and muon charge (a la tag and probe).

A.1.1 Selection and candidates

- **ATLAS Good Run list requirement:** All subsystems passing online data quality checks.
 - $\int \mathcal{L} dt = 8.7 \text{ pb}^{-1}$: **Trigger L1_MU6 or EF_MU10**
- **Objects Requirements:**
 - Muons
 - * ID+MS $\rightarrow$ STACO and MuID reconstruction algorithms.
 - * $P_T^\mu > 15 \text{ GeV}$ and $|\eta| < 2.4$
 - * $P_T^{MS} > 10 \text{ GeV}$
 - * $|P_T^{ID} - P_T^{MS}| < 15 \text{ GeV}$
 - * Close to at least one GOOD vertex in z : $|z_0 - z_{vtx}| < 10 \text{ mm}$
- **At least two high P_T muons:** $P_T > 20 \text{ GeV}$
- **Isolation:** Relative track isolation $\frac{\sum_{\text{cone40}} P_T^{ID}}{P_T} < 0.2$
- **Opposite charged, and mass window:** $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$

Number of event candidates with 8.7 pb^{-1} .

- Staco: 2883
 - Both μ in barrel: 817
 - One μ in barrel one in endcap: 1444
 - Both μ in endcaps: 622
 - Restricting to $|\eta| < 2$ (**no CSC**): 2261
- MuID: 2921
 - Both μ in barrel: 837
 - One μ in barrel one in endcap: 1468
 - Both μ in endcaps: 616
 - Restricting to $|\eta| < 2$ (**no CSC**): 2308
- + MC simulation: Pythia (with PileUp) $\rightarrow$ normalised to data entries (no luminosity dependency).

A.1.2 Additional results

Best fitted Z boson invariant mass:

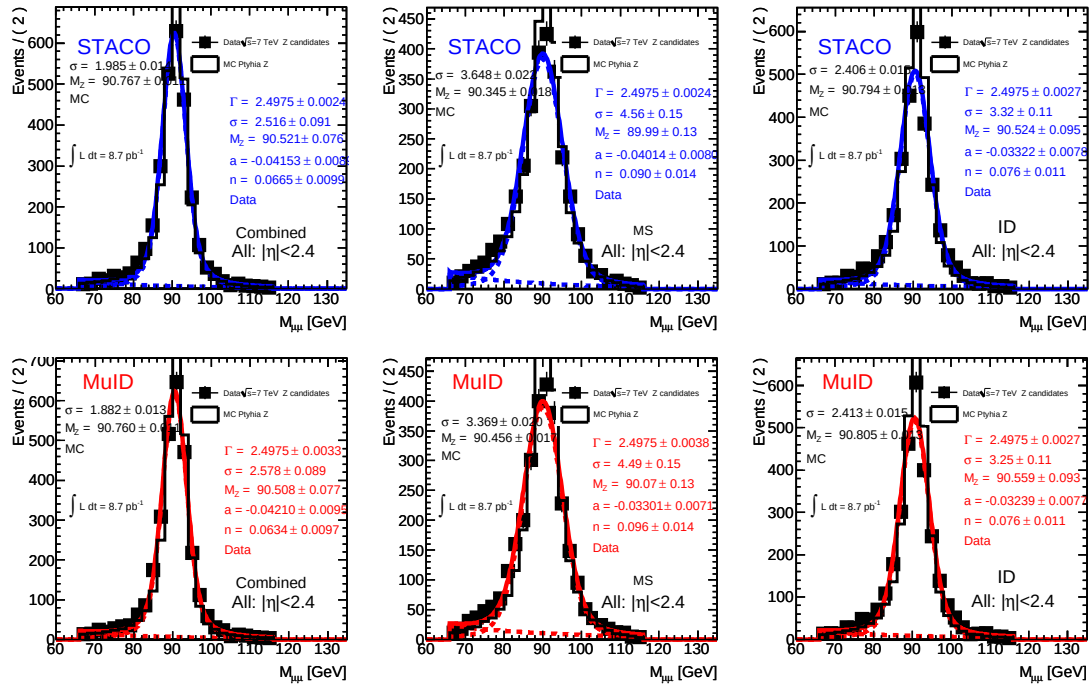


Figure A.1: Resolution studies on $Z \rightarrow \mu\mu$ events for measurements given by the ID only, MS only and their combination. Both STACO and MuID muon reconstruction algorithms are studied.

Function of η : barrel-barrel, barrel-endcap, endcap-endcap

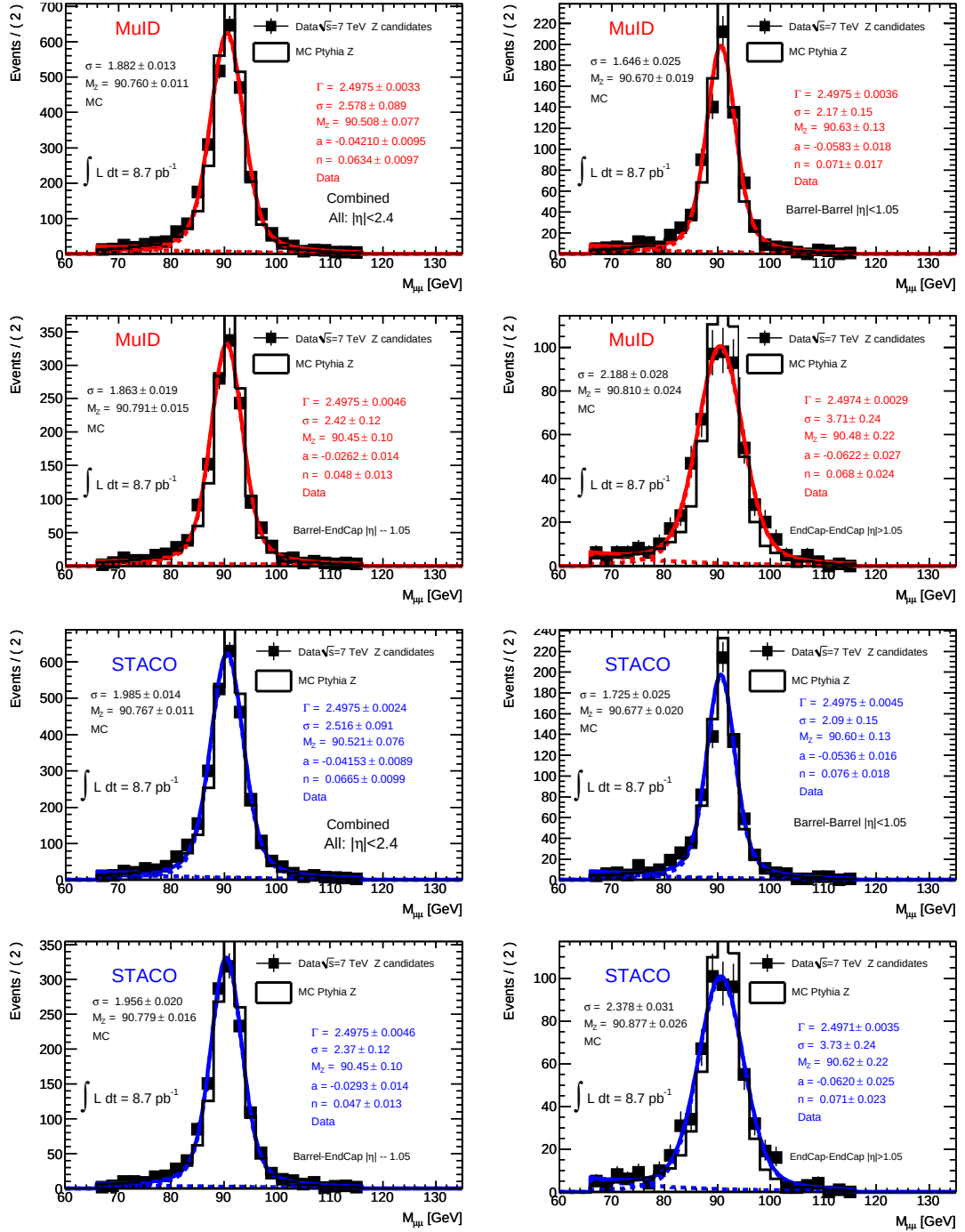


Figure A.2: Resolution studies on $Z \rightarrow \mu\mu$ events for the various possible configurations of muon pairs landing on the barrel and endcap regions.

Resolution and best m_Z fit values for the different muon pair barrel-endcap η configurations:

Table A.1: Resolution studies on $Z \rightarrow \mu\mu$ events

		STACO		MuID	
		DATA	MC	DATA	MC
Resolution [GeV]					
ALL	Combined P_T^μ	2.52 ± 0.09	1.99 ± 0.01	2.58 ± 0.09	1.88 ± 0.01
	Muon Spect. P_T^μ	4.56 ± 0.15	3.65 ± 0.02	4.49 ± 0.15	3.37 ± 0.02
	Inner Track P_T^μ	3.32 ± 0.11	2.41 ± 0.01	3.25 ± 0.11	2.41 ± 0.01
$ \eta < 2$	Combined P_T^μ	2.40 ± 0.10	1.93 ± 0.02	2.45 ± 0.10	1.85 ± 0.01
	Muon Spect. P_T^μ	4.48 ± 0.16	3.69 ± 0.02	4.31 ± 0.15	3.43 ± 0.02
	Inner Track P_T^μ	2.77 ± 0.11	2.12 ± 0.02	2.74 ± 0.11	2.14 ± 0.02
Barrel-Barrel	Combined P_T^μ	2.09 ± 0.15	1.72 ± 0.02	2.17 ± 0.15	1.65 ± 0.02
	Muon Spect. P_T^μ	3.54 ± 0.20	3.00 ± 0.03	3.38 ± 0.18	2.82 ± 0.03
	Inner Track P_T^μ	2.33 ± 0.18	1.88 ± 0.03	2.33 ± 0.18	1.92 ± 0.03
Barrel-Endcap	Combined P_T^μ	2.37 ± 0.12	1.96 ± 0.02	2.42 ± 0.12	1.86 ± 0.02
	Muon Spect. P_T^μ	4.70 ± 0.21	3.77 ± 0.03	4.64 ± 0.22	3.43 ± 0.03
	Inner Track P_T^μ	3.27 ± 0.15	2.38 ± 0.00	3.16 ± 0.14	2.35 ± 0.02
Endcap-Endcap	Combined P_T^μ	3.73 ± 0.24	2.38 ± 0.03	3.71 ± 0.24	2.19 ± 0.03
	Muon Spect. P_T^μ	5.99 ± 0.42	4.32 ± 0.05	6.20 ± 0.39	4.02 ± 0.05
	Inner Track P_T^μ	5.43 ± 0.39	3.25 ± 0.04	5.28 ± 0.38	3.24 ± 0.04
Best m_Z fit [GeV]					
ALL	Combined P_T^μ	90.52 ± 0.08	90.77 ± 0.01	90.51 ± 0.08	90.76 ± 0.01
	Muon Spect. P_T^μ	89.99 ± 0.13	90.35 ± 0.02	90.07 ± 0.13	90.46 ± 0.02
	Inner Track P_T^μ	90.52 ± 0.10	90.79 ± 0.01	90.56 ± 0.09	90.81 ± 0.01
$ \eta < 2$	Combined P_T^μ	90.40 ± 0.08	90.73 ± 0.01	90.39 ± 0.08	90.73 ± 0.01
	Muon Spect. P_T^μ	89.80 ± 0.14	90.27 ± 0.02	89.97 ± 0.14	90.39 ± 0.02
	Inner Track P_T^μ	90.50 ± 0.09	90.82 ± 0.01	90.51 ± 0.09	90.81 ± 0.01
Barrel-Barrel	Combined P_T^μ	90.60 ± 0.13	90.68 ± 0.02	90.63 ± 0.13	90.67 ± 0.02
	Muon Spect. P_T^μ	90.36 ± 0.19	90.29 ± 0.03	90.47 ± 0.18	90.32 ± 0.03
	Inner Track P_T^μ	90.58 ± 0.14	90.82 ± 0.02	90.59 ± 0.14	90.77 ± 0.02
Barrel-Endcap	Combined P_T^μ	90.45 ± 0.10	90.78 ± 0.02	90.45 ± 0.10	90.79 ± 0.02
	Muon Spect. P_T^μ	89.90 ± 0.18	90.34 ± 0.03	89.91 ± 0.18	90.50 ± 0.02
	Inner Track P_T^μ	90.43 ± 0.13	90.81 ± 0.08	90.48 ± 0.12	90.85 ± 0.02
Endcap-Endcap	Combined P_T^μ	90.62 ± 0.22	90.88 ± 0.03	90.48 ± 0.22	90.81 ± 0.02
	Muon Spect. P_T^μ	89.62 ± 0.35	90.46 ± 0.04	89.73 ± 0.36	90.56 ± 0.04
	Inner Track P_T^μ	90.58 ± 0.32	90.75 ± 0.03	90.64 ± 0.31	90.77 ± 0.03

Resolution and best m_Z fit value as function of $|\eta|$, cumulative

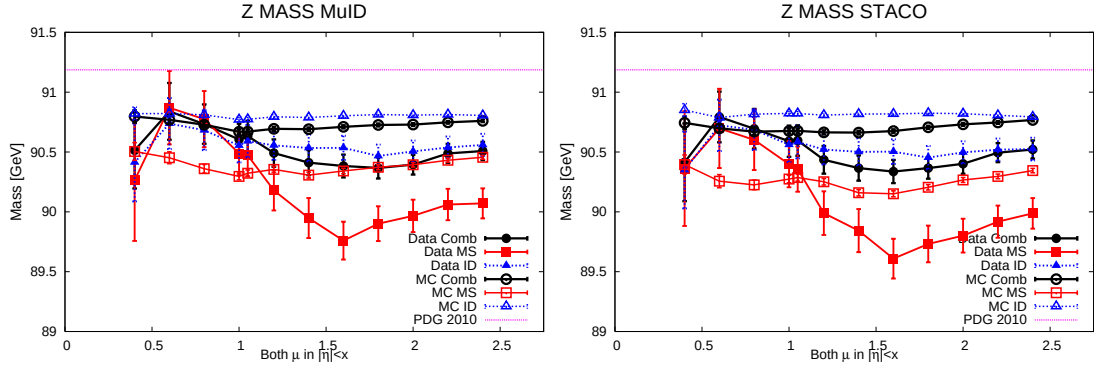


Figure A.3: Resolution studies on $Z \rightarrow \mu\mu$ events as function of cumulative pseudorapidity.

Barrel tag + μ in endcap separating in ϕ

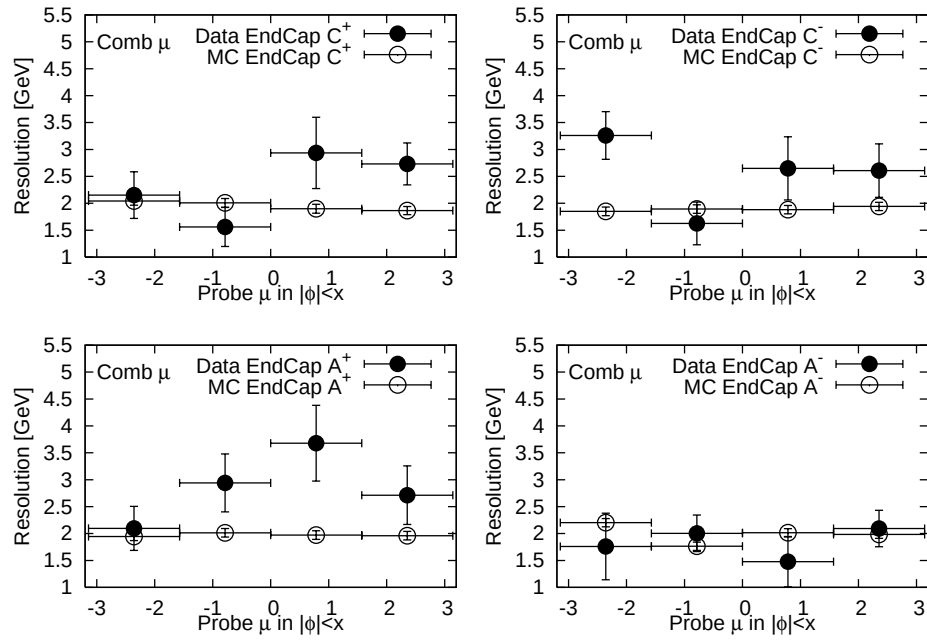


Figure A.4: Resolution studies on $Z \rightarrow \mu\mu$ events for different quadrants on ϕ .

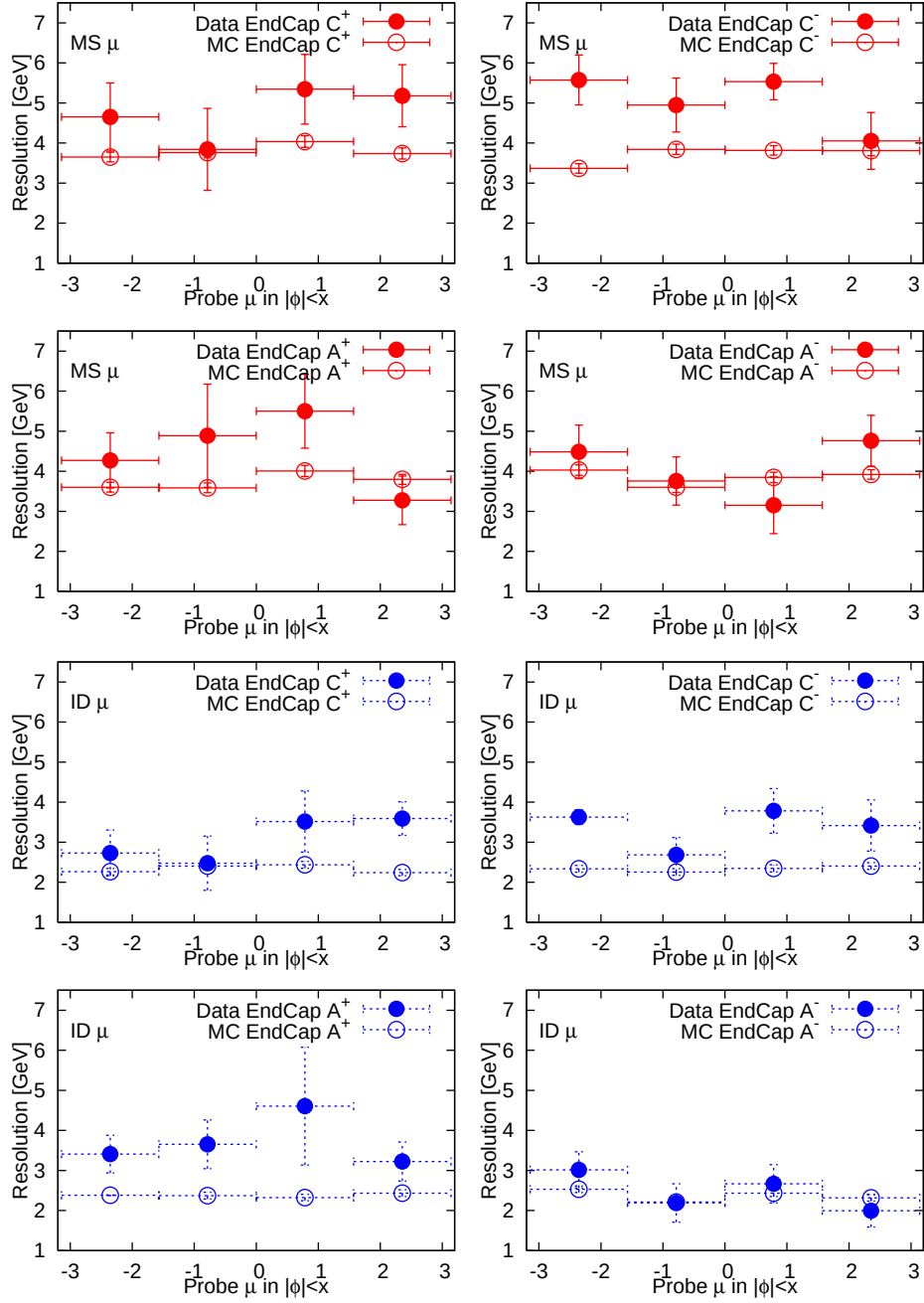


Figure A.5: Resolution studies on $Z \rightarrow \mu\mu$ events for different quadrants on ϕ for ID/MS measurements.

Barrel tag + μ probed in endcap, separating in muon charge and endcap side.

Probe muon $\rightarrow 0 < \phi < \pi/2$ - MS

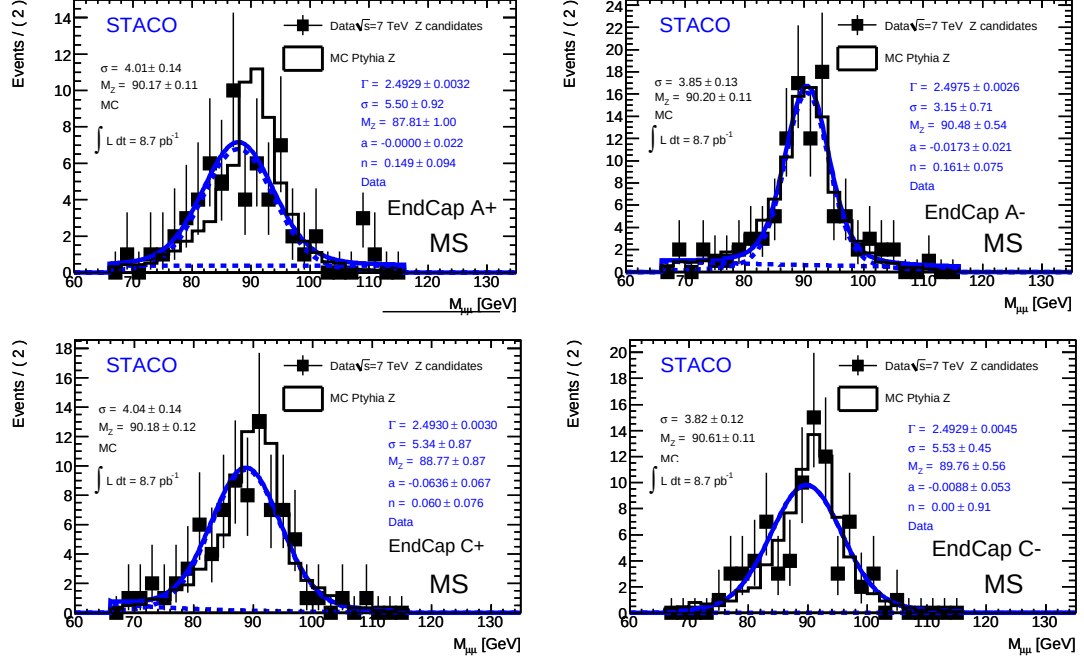


Figure A.6: Example of resolution studies on $Z \rightarrow \mu\mu$ events for tag and probed muons separated as function of muon charged and endcap side.

A.2 Validation of the PDF Reweighting Technique

This appendix documents studies which check the accuracy of the PDF reweighting technique by comparing results from Monte Carlo samples generated with a center-of-mass energy of 14 TeV and reweighted to 10 TeV, and generated at 10 TeV and reweighted to 7 TeV; against similar samples generated using a center-of-mass energy of the specific $\sqrt{s}$ directly. Relevant details of the dedicated samples, such as the choice of PDF set, were chosen to be the same as for the reweighted samples for the sake of consistency. These set of checks were made on the frame of both the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ and the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ analysis.

A.2.1 From 14 TeV to 10 TeV for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ channel

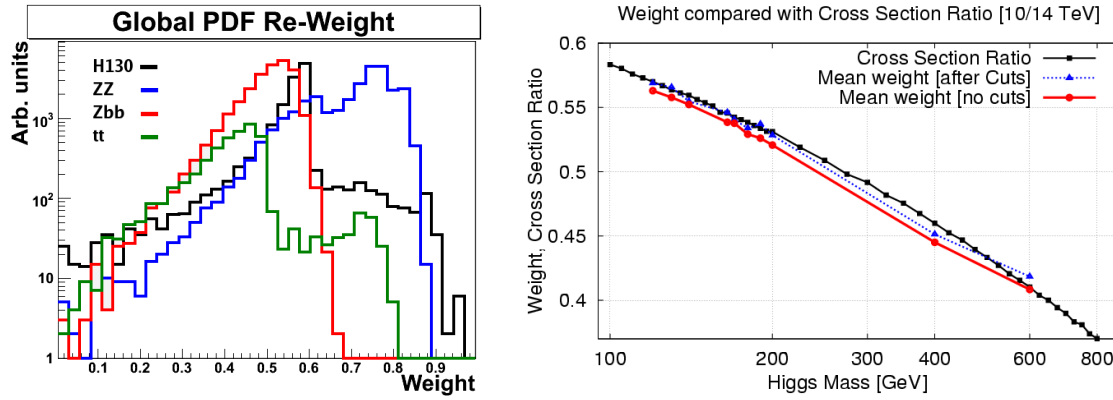


Figure A.7: Left: it is shown the distributions of the PDF weights that were applied to scale the samples from 14 to 10 TeV. Right: comparison of the SM Higgs boson cross-section ratio and the mean value of the weight distribution for different mass points.

In order to estimate the impact of a run at 10 TeV instead of 14 TeV using the existing MC, it was necessary to re-weight the samples event by event at the level of PDF. In Fig A.7 left, it is shown the distributions of the PDF re-weights for signal and backgrounds. It is also possible to see how the re-weight predicts a more important decrease in the Higgs boson signal the Zbb and $t\bar{t}$ when compared with the irreducible ZZ background.

The validation of this weighting procedure was done from the normalization point of view. In Fig. A.7 right it is shown the ratio of the total cross sections $\frac{\sigma_{NLO}(\sqrt{s}=10\text{TeV})}{\sigma_{NLO}(\sqrt{s}=14\text{TeV})}$ together with the mean distribution of the PDF re-weight, calculated before and after the kinematic selection. Something similar was done for the direct production of ZZ , using the MCFM package.

A.2.2 From 10 TeV to 7 TeV for the $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ channel

Figures A.8 through A.13 show comparisons of the distributions of several kinematic variables in gluon fusion signal events generated with Pythia using a Higgs boson mass of 165 GeV. The distributions obtained by applying the PDF reweighting technique to samples generated with a center-of-mass energy of 10 TeV agree well with those obtained by generating events directly with a center-of-mass energy of 7 TeV. Figures A.11 and A.12 show similar comparisons for samples of Pythia dijet events.¹ For both processes, the shape and normalization obtained using PDF reweighting of the 10 TeV sample to 7 TeV agrees well with the MC sample generated with a center-of-mass energy of 7 TeV. Plots are normalized to predicted cross-section (in fb). The black curves show the results for 10 TeV, the red curves show the results for 7 TeV obtained by using PDF reweighting on the 10 TeV samples, and the blue curves show the result for 7 TeV using a Monte Carlo sample generated with a center-of-mass energy of 7 TeV.

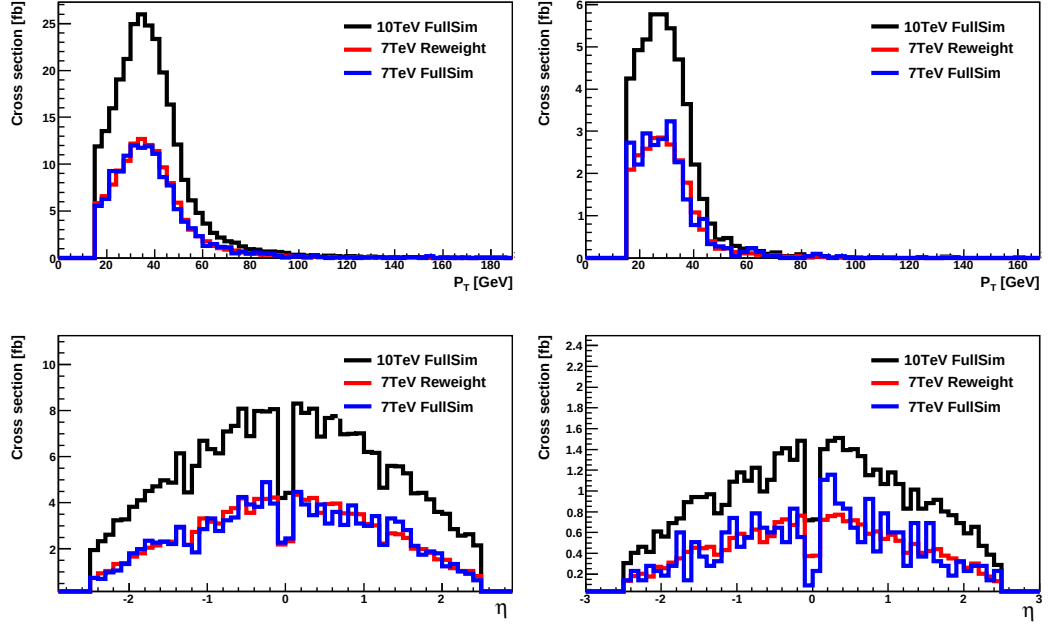


Figure A.8: The p_T (top) and $|\eta|$ (bottom) of the leading (left) and subleading (right) muon in two-muon gluon fusion signal events with $m_H = 165$ GeV.

¹The dijet samples used here include the “J2” cuts on the p_T of the event, $35 < p_T < 70$ GeV, where p_T is defined in the rest frame of the hard interaction.

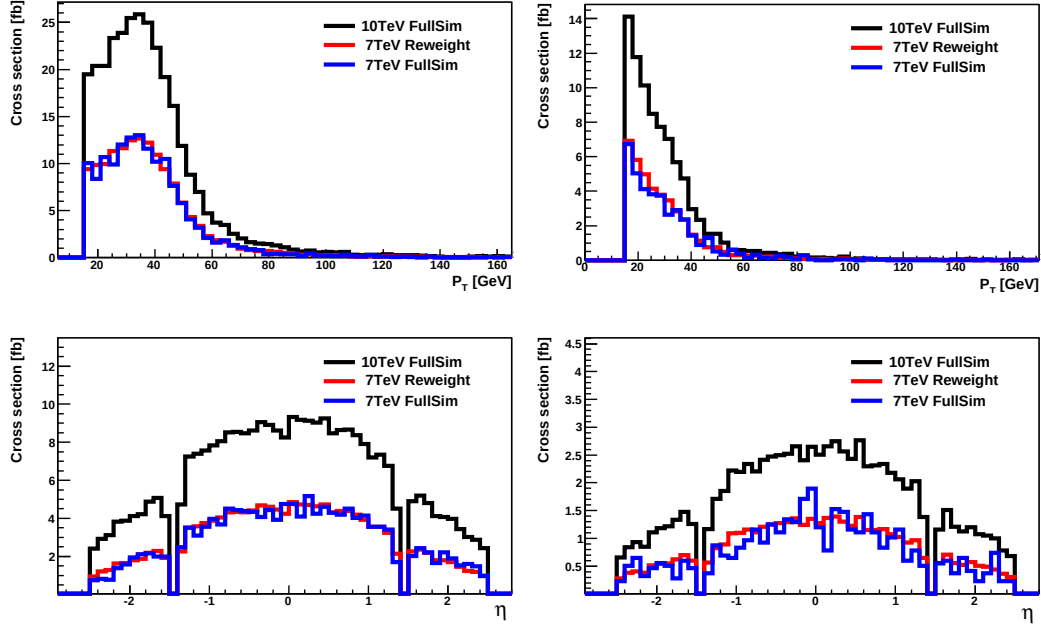


Figure A.9: The p_T (top) and $|\eta|$ (bottom) of the leading (left) and subleading (right) electron in two-electron gluon fusion signal events with $m_H = 165$ GeV.

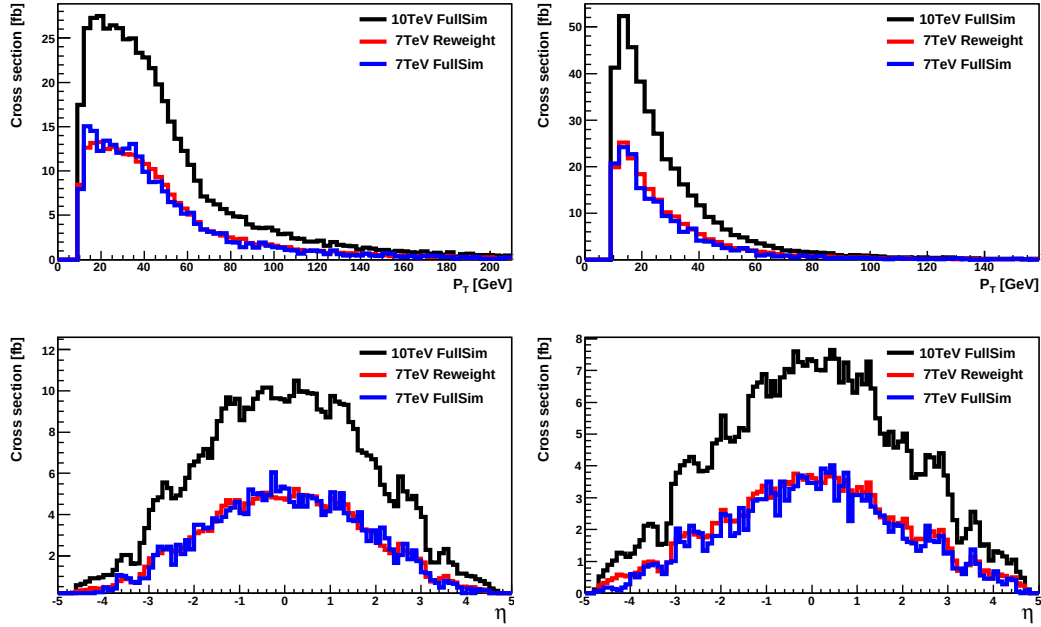


Figure A.10: The p_T (top) and $|\eta|$ (bottom) of the leading (left) and subleading (right) jet in two-lepton gluon fusion signal events with $m_H = 165$ GeV.

A.2. Validation of the PDF Reweighting Technique

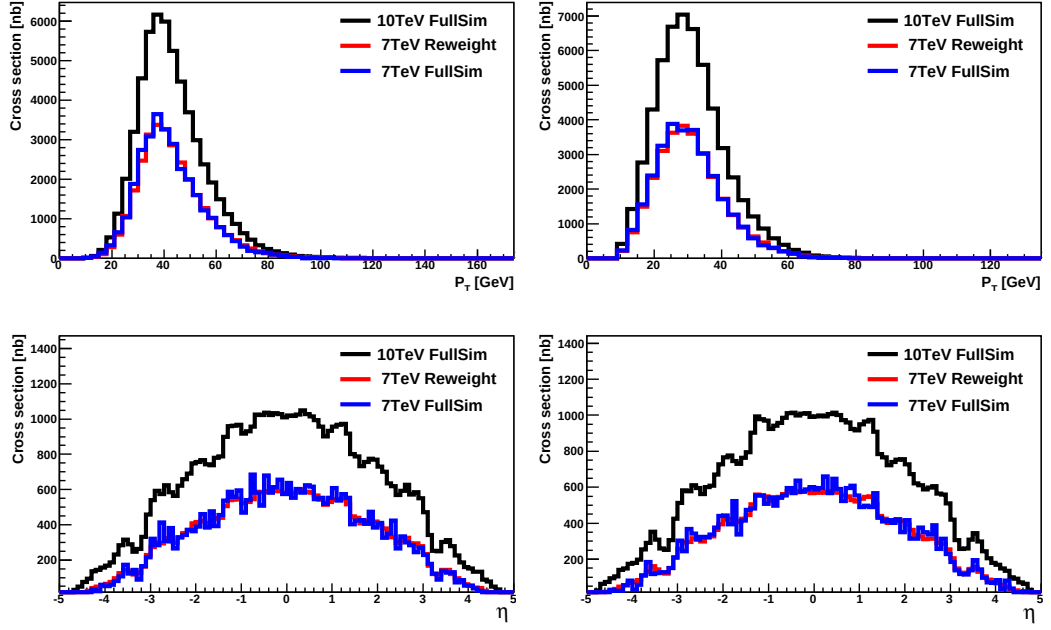


Figure A.11: A comparison of the distributions of the p_T (top) and η (bottom) of the leading (left) and subleading (right) jets in Pythia dijet ("J2") events.

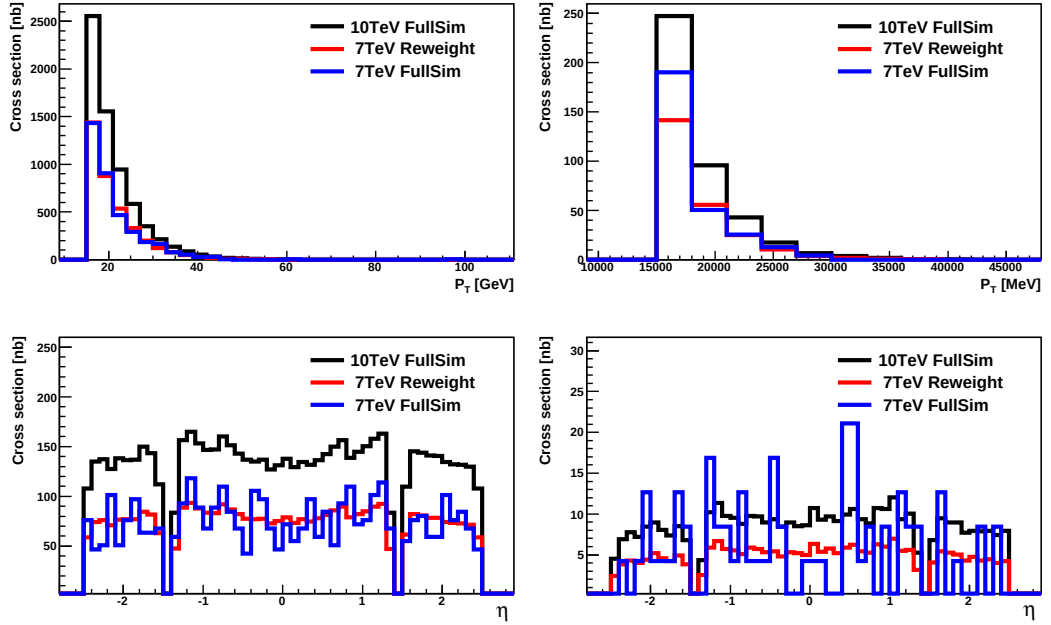


Figure A.12: A comparison of the distributions of the p_T (top) and η (bottom) of the leading (left) and subleading (right) leptons in Pythia dijet ("J2") events.

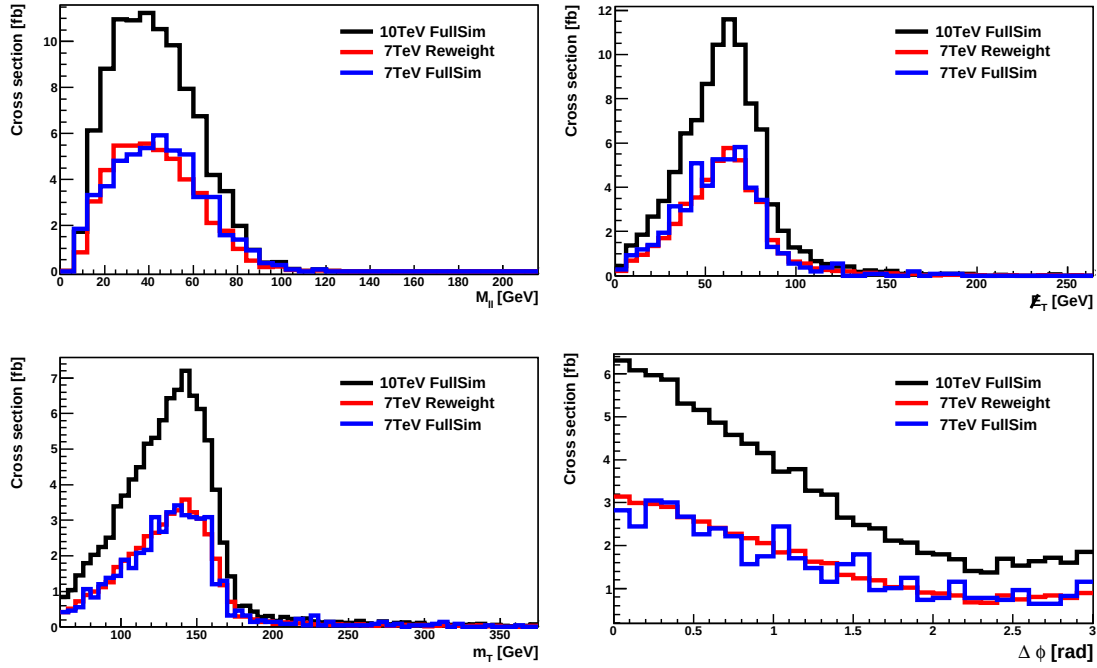


Figure A.13: A comparison of the distributions of several discriminating variables important to the $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ analysis. Upper left: the dilepton invariant mass $m_{\ell\ell}$. Upper right: the missing transverse momentum p_T^{miss} . Lower left: the transverse mass m_T . Lower right: the dilepton opening angle in the transverse plane, $\Delta\phi_{\ell\ell}$.

A.3 Limit settings techniques

Frequentist Limit Setting and Hypothesis Testing

The Likelihood is defined as the product of Poisson probabilities in the signal region and each of the control samples. This function is maximised over a space of parameters including normalisations for each of the backgrounds, the ratios of cross-sections for each of the background normalisations, plus two additional parameters corresponding to the systematic error on the signal efficiency and the uncertainty in the luminosity. The systematic error on the signal efficiency is typically the sum in quadrature of contributions from the detector effects such as jet energy scale uncertainty, and the theoretical uncertainties.

The normalisation of the different backgrounds, as well as the uncertainty parameters for the signal efficiency and the luminosity uncertainty, are constrained to be close to their predicted values by introducing Gaussian terms to the Likelihood function; the centre of each Gaussian constraint term is varied within its uncertainties from outcome to outcome. The Likelihood function is maximised several times, once with the signal normalisation, a free parameter, and again with the signal normalisation fixed to each of a set of specified values of $\mu = \sigma_{\text{excluded}}/\sigma_{\text{SM}}$. The Likelihood Ratio is defined as a function of μ by taking $\lambda(\mu) = L_{s \text{ free}}/L_{s=\mu}$ for each of these values of μ .

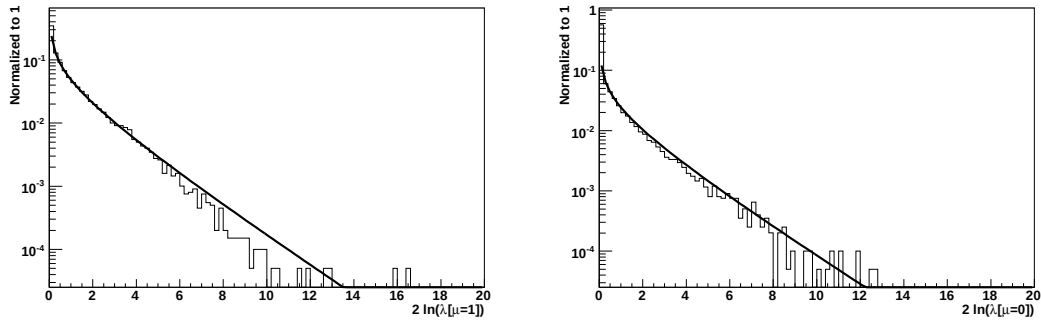


Figure A.14: Comparisons between the Likelihood Ratio distributions obtained using toy MC and the asymptotic approximations used in evaluating p -values. Left: the distribution for the Likelihood Ratio under the signal-plus-background hypothesis when signal is actually present. A χ^2 curve with one degree of freedom is overlaid for comparison. Right: the distribution for the Likelihood Ratio under the background-only hypothesis when signal is actually not present. A $\frac{1}{2}\chi^2$ distribution is overlaid for comparison.

For a specified value of μ , the expected p -value is obtained by computing the probability that an outcome generated using the given value of μ as the true value has $\lambda(\mu)$ greater than the observed value of $\lambda(\mu)$. Figure A.14 shows that the p -value can be accurately estimated using the approximation that $2\ln(\lambda)$ is distributed as a χ^2 with one degree of freedom for $\mu \gg 0$ and as the sum of a delta function centred at zero and a χ^2 with one degree of freedom (with each

component normalised to an area of 1/2) for $\mu = 0$.

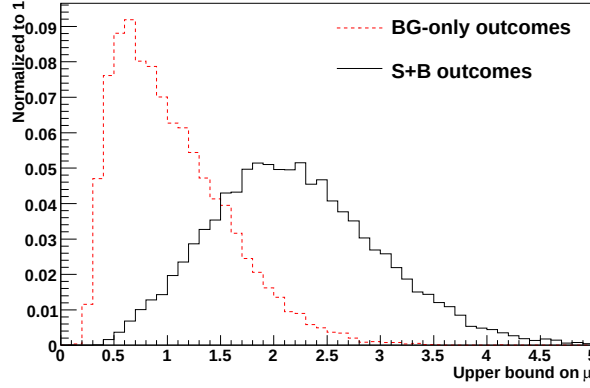


Figure A.15: Frequentist upper bound for a sample of toy MC outcomes where the Higgs boson mass Hypothesis was 160 GeV and the integrated luminosity was 200 pb^{-1}

The value of μ for which the Likelihood Ratio is smallest is known as the preferred value, μ_0 ; the upper bound for a given Higgs boson mass hypothesis in a given outcome is the smallest value of $\mu > \mu_0$ for which the p -value is less than or equal to 0.05. Figure A.15 shows the sampling distribution of the obtained upper bound in sets of toy MC outcomes with and without a Standard Model signal present at the truth level, for a Higgs boson mass of 170 GeV and an integrated luminosity of 200 pb^{-1} . Approximately 5% of the signal plus background distribution lies below $\mu = 1$. The right plot shows the behaviour of this fraction as a function of μ for several values of the Higgs boson mass. The behaviour is qualitatively similar to the corresponding plot for the Bayesian method, but the curves are generally closer to the ideal value of 0.05.

Bayesian Limit Setting and Model Selection

In a Bayesian analysis, one begins with some *a priori* belief about parameters like the signal and background normalisations, one writes down a “model density” describing the experiment, and one obtains a “posterior credibility distribution” from Bayes’ rule:

$$P(\lambda|X) \sim P(X|\lambda)\pi(\lambda) \quad (\text{A.1})$$

where λ represents the parameters of the model (in this case the normalisation parameters for signal and background), X represents the observed (pseudo-)data in any given outcome, $\pi(\lambda)$ is the prior credibility distribution, $P(X|\lambda)$ is the model density, and $P(\lambda|X)$ is the posterior credibility distribution, normalised to 1. In the presented analyses, the prior credibility distribution $\pi(\lambda)$ is chosen to be a product of several components, modelled by normal functions controlling the normalisation of the different background processes.

No correlation is assumed among any of these parameters; they are all taken to be independent. For historical reasons, systematic uncertainties on the signal efficiency and integrated luminosity are not taken into account in the Bayesian results presented here. The model density is a product of the Poisson probabilities in the signal region and each of the control regions; the total “expected” number of events in each control region is taken to be equal to the observed number of events in that region, and the normalisation parameter for the corresponding background is set so that the total, including known contaminations, agrees with the number of observed events.

The posterior distribution is sampled with a set of test points drawn from the prior distribution. The resulting points are histogrammed in the signal normalisation parameter in units of the SM cross-section, $\mu = \sigma/\sigma_{SM}$; that is, all other parameters are integrated out. The 95% confidence level upper bound for a given outcome is taken to be the value of μ for which the integral of the posterior from μ_{bound} to infinity is only 5% of the distribution.

Figure A.16 shows the obtained upper bounds for samples of 20000 toy MC outcomes with and without a Standard Model ($\mu = 1$) Higgs boson signal present at the truth level, for a representative Higgs boson mass hypothesis of 170 GeV with an integrated luminosity of 200 pb^{-1} . Approximately 1.2% of the signal-plus-background distribution lies below $\mu = 1$.

The obtained limits are therefore conservative. The exclusion limit figures in the following show the upper bound as a function of m_H for integrated luminosities of 200 pb^{-1} and 1 fb^{-1} . The black line corresponds to the median of the background-only distribution in Fig. 6.19; the green and yellow bands show the $\pm 1\sigma$ and $\pm 2\sigma$ bands around this value, as obtained from the distribution of the obtained limit in background-only outcomes.

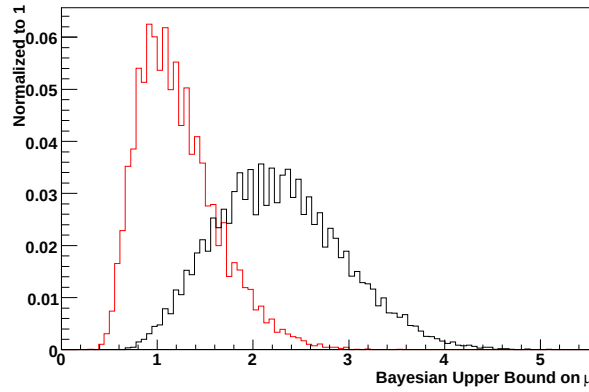


Figure A.16: Bayesian upper bound for a sample of toy MC outcomes where the Higgs boson mass Hypothesis was 160 GeV and the integrated luminosity was 200 pb^{-1} .

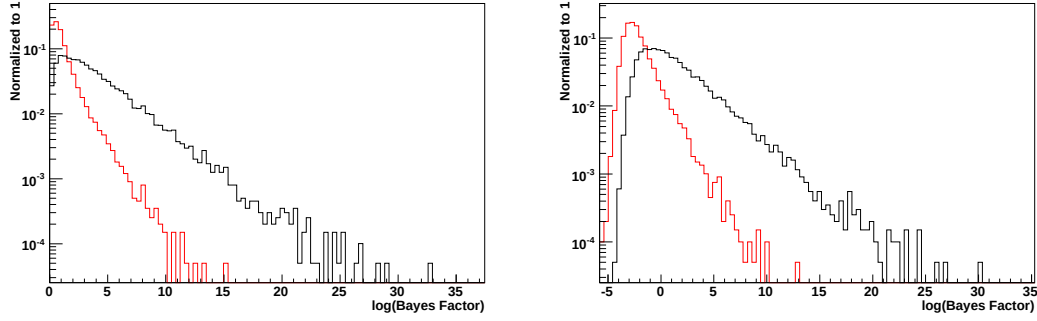


Figure A.17: Distribution of Bayes factors in signal-plus-background (black) and background-only (red) outcomes. Left: K_{max} . Right: K_u .

Model selection in a Bayesian framework is done using a Bayes factor,

$$K(s_0) = \frac{\int P(\lambda, s = s_0 | X) d\lambda}{\int P(\lambda, s = 0 | X) d\lambda} \quad (\text{A.2})$$

where s is the signal normalisation parameter, s_0 is some particular value of s , and the integrals are only over the parameters other than s . This study considers two variants on the Bayes factor:

- K_{max} , the largest value of $K(s_0)$ for any s_0 , and
- $K_u = \int_0^{\sigma_{max}} K(s_0) ds_0$, where σ_{max} is taken to be 15 times the Standard Model cross-section times the luminosity. This corresponds to assuming a uniform prior on the signal normalisation in the range from zero to σ_{max} .

The distributions of K_{max} and K_u for samples of toy MC outcomes with and without a Standard Model Higgs boson signal present at the truth level, again for a representative Higgs boson mass hypothesis of 160 GeV with an integrated luminosity of 200 pb⁻¹, are shown in Figure A.17. The expected significance for this mass and luminosity is only about 1.6 σ ; since $m_H = 160$ GeV is expected to be one of the strongest mass points for this channel, it is therefore not appropriate to make a significance plot.

A.4 $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ additional informamtion

A.4.1 Object and event kinematics

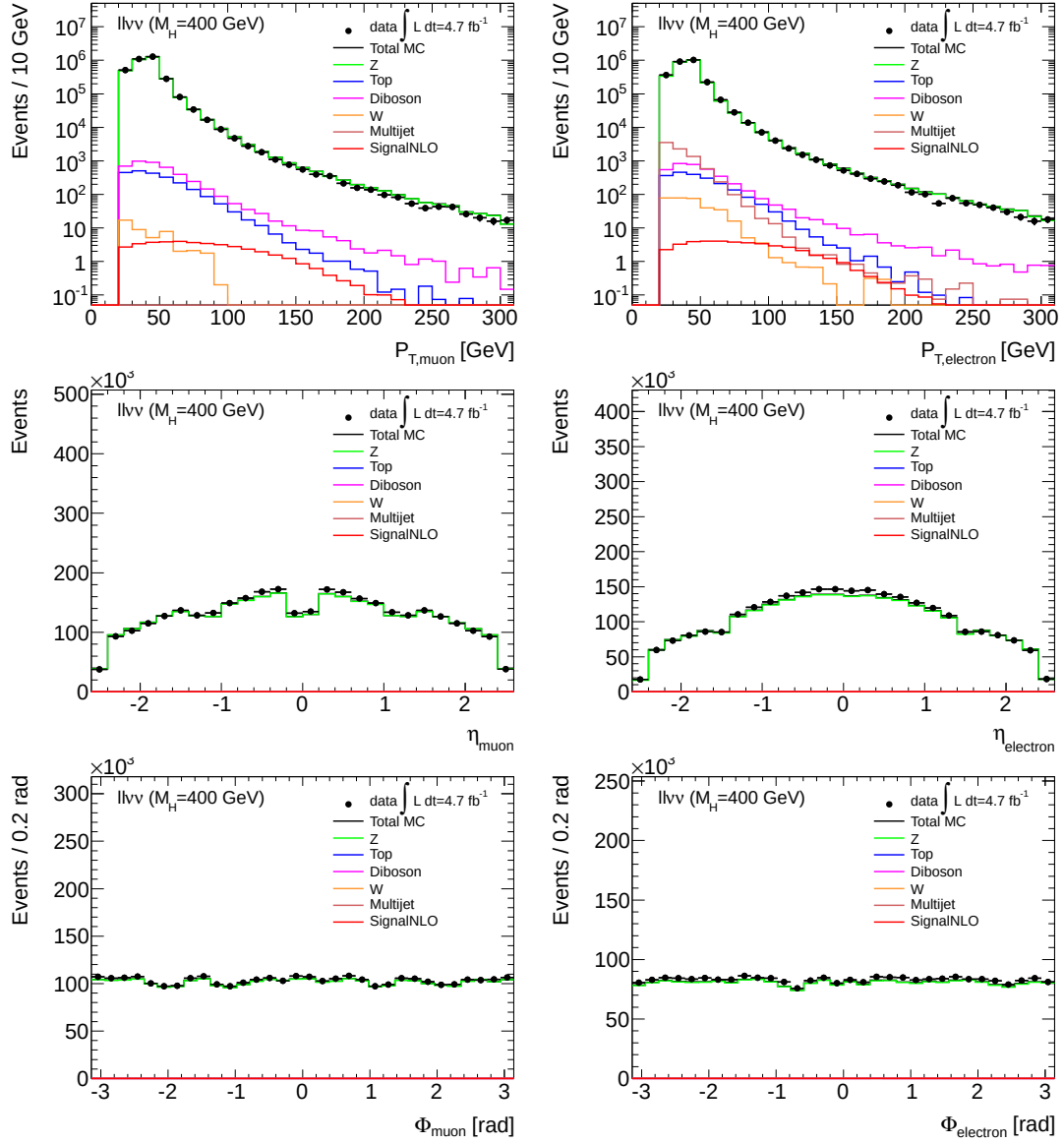


Figure A.18: P_T , η and ϕ distributions of the two leptons.

A.4.2 Cut optimisation

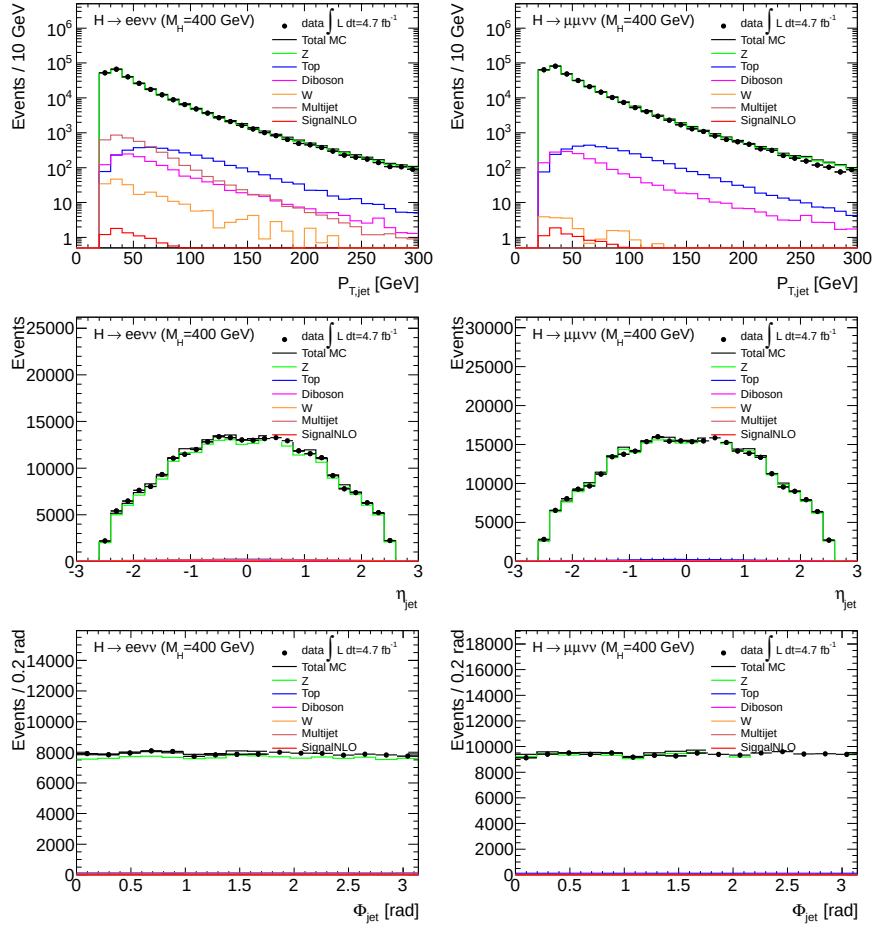


Figure A.19: The $P_T(\text{Top})$, $\eta(\text{Centre})$ and $\phi(\text{Bottom})$ distributions of the highest P_T jet in events with exactly two electrons (Left) or two muons(Right). Only jets with $P_T > 25$ GeV and $|\eta| < 2.5$ are included.

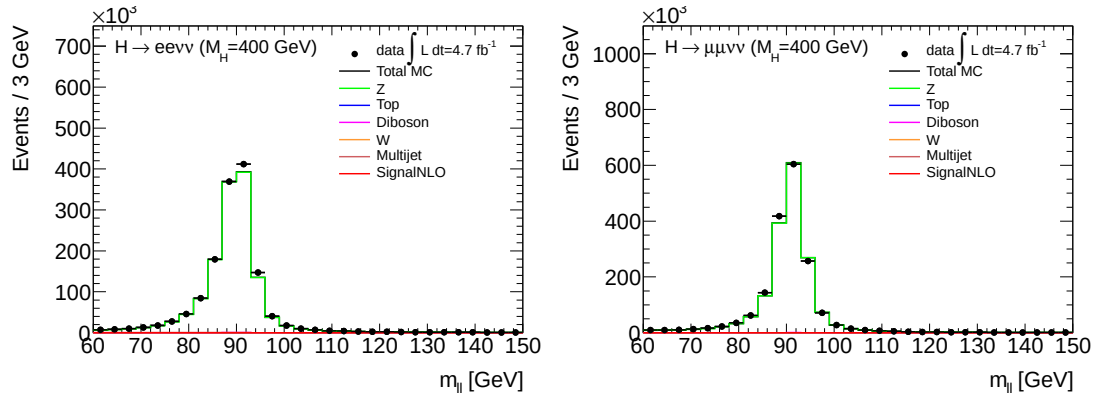


Figure A.20: The dilepton invariant mass for the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel in the (Left) electron and (Right) muon channels.

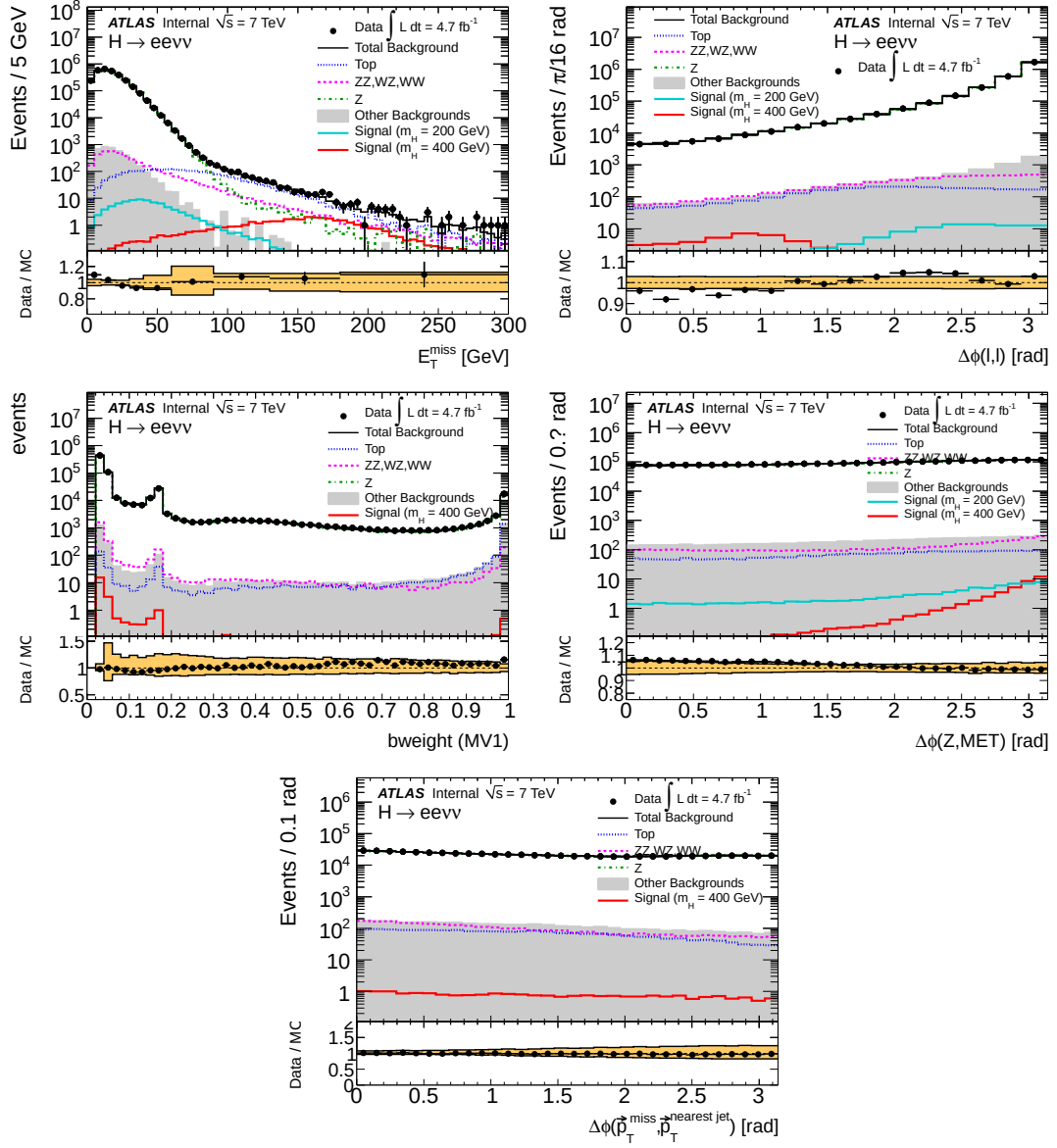


Figure A.21: Kinematic distributions relevant to the $H \rightarrow ZZ \rightarrow e^+e^-\nu\bar{\nu}$ analysis for the Higgs boson signal and the main backgrounds: (Left) E_T^{miss} , (Right) the opening angle between the leptons, $\Delta\phi_{ll}$, (c) the maximum MV1 b -tagging weight, (d) the opening angle between the lepton pair and the E_T^{miss} , $\Delta\phi_{ll,\text{MET}}$ and (e) the opening angle between the E_T^{miss} and the nearest jet, $\Delta\phi_{\text{MET},\text{Jet}}$, in the event. The signal sample shown corresponds to a Higgs boson with $m_H = 400$ GeV. The bottom plot shows the ratio between data and the combined MC background samples as well as a band formed by adding in quadrature all systematic uncertainties.

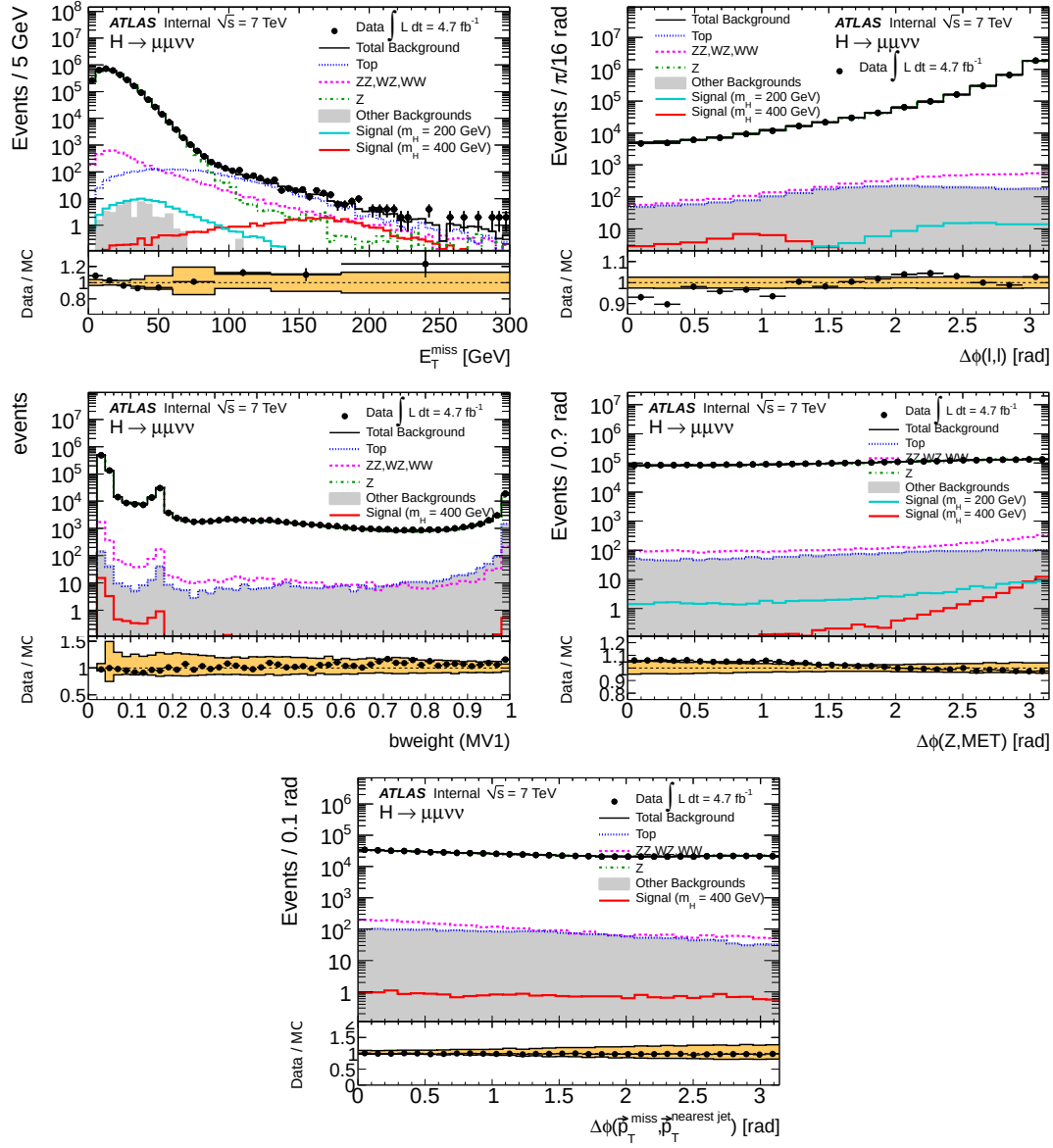


Figure A.22: Kinematic distributions relevant to the $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$ analysis for the Higgs boson signal and the main background: (Top Left) E_T^{miss} , (Top Right) the opening angle between the leptons, $\Delta\phi_{ll}$, (Centre Left) the maximum MV1 b -tagging weight, (Centre Right) the opening angle between the lepton pair and the E_T^{miss} , $\Delta\phi_{ll,MET}$ and (Bottom) the opening angle between the E_T^{miss} and the nearest jet, $\Delta\phi_{MET,Jet}$, in the event. The signal sample shown corresponds to a Higgs boson with $m_H = 400$ GeV. The bottom plot shows the ratio between data and the combined MC background samples as well as a band formed by adding in quadrature all systematic uncertainties.

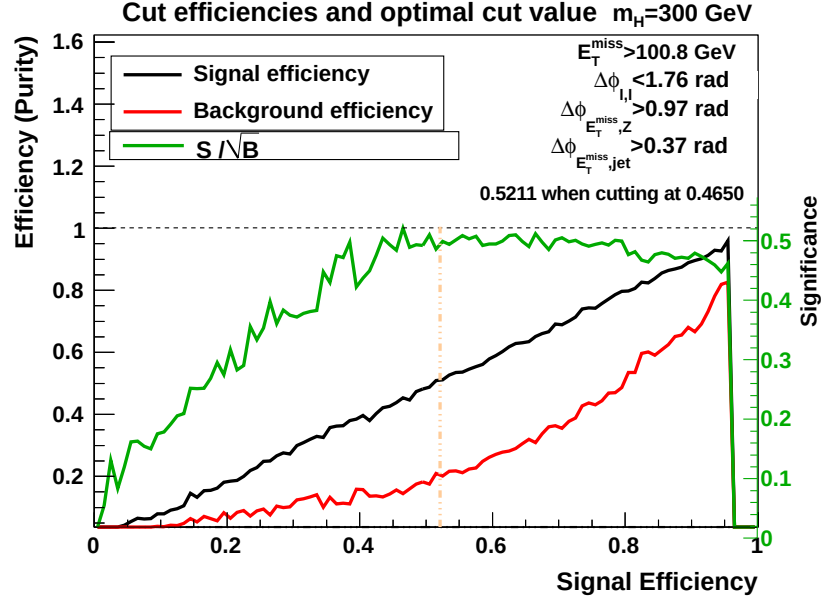


Figure A.23: The rocking curve for different cut total efficiencies. The largest significance is reached when the signal efficiency is about 50%. It corresponds to cuts on the $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\ell\ell}) > 1$, and $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 0.4$. This values were reoptimised later to cope with the larger luminosity conditions, where more jet activity was expected.

Table A.2: Cutoffs for the $H \rightarrow ZZ \rightarrow e^+e^- \nu\bar{\nu}$ (Top) and $H \rightarrow ZZ \rightarrow \mu^+\mu^- \nu\bar{\nu}$ (Bottom) channels for $m_H = 200$ GeV for low pileup period. The Monte Carlo H signal column only contains signal events in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay mode. Cross talk from other Higgs boson decay modes is not included in this table. The numbers for the data and data-driven multijet background are not reported before the 2 lepton requirement since the analysis is performed on a skimmed data sample which already has a dilepton requirement. The uncertainties shown are statistical only. Note that corrections to event weights to account for data MC differences in the selection efficiencies of leptons and the b -tagging are included at all stages.

Channel: 2e2nu						
Sample	Data	H	$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet
All	–	138.42 ± 1.14	7429316.50 ± 2130.98	37318268.00 ± 15095.26	298977.34 ± 188.46	–
Vertex	–	138.41 ± 1.14	7426931.50 ± 2130.68	37298488.00 ± 15091.07	298975.12 ± 188.46	–
Jet cleaning	–	137.98 ± 1.14	7401038.00 ± 2127.45	37237056.00 ± 15079.59	298351.38 ± 188.25	–
Trigger	–	45.29 ± 0.64	1793964.62 ± 1085.92	6194778.50 ± 6014.80	73696.33 ± 90.15	–
2 leptons	–	20.99 ± 0.43	685885.69 ± 676.48	360.57 ± 20.63	2256.90 ± 12.27	–
$ m_{\ell\ell} - m_Z < 15$ GeV	647677	20.06 ± 0.43	626262.88 ± 647.26	79.56 ± 8.78	506.34 ± 5.78	1962.94 ± 8.41
b -tagging cut	617159	18.00 ± 0.41	596689.25 ± 635.92	72.01 ± 8.62	51.58 ± 2.05	1809.86 ± 8.07
E_t^{miss}	198	2.50 ± 0.13	120.64 ± 8.48	5.52 ± 2.30	21.38 ± 1.20	3.17 ± 0.34
$\Delta\phi_{ll}$ cuts	88	1.42 ± 0.09	38.68 ± 4.23	5.28 ± 2.28	13.65 ± 0.97	1.58 ± 0.24
$\Delta\phi(Z, E_t^{\text{miss}})$ cut	88	1.42 ± 0.09	38.68 ± 4.23	5.28 ± 2.28	13.65 ± 0.97	1.58 ± 0.24
$\Delta\phi(E_T^{\text{miss}}, jet)$ cut	62	1.27 ± 0.09	21.46 ± 3.56	4.63 ± 2.23	9.86 ± 0.83	1.08 ± 0.20
Total BG						
					22580.90 ± 67.71	–
					22578.22 ± 67.71	–
					22518.51 ± 67.62	–
					8349.08 ± 38.50	–
					1286.06 ± 11.47	–
					891.03 ± 10.88	629702.81 ± 647.49
					658.49 ± 8.85	599281.19 ± 636.09
					59.86 ± 1.29	210.56 ± 8.97
					41.42 ± 1.07	100.61 ± 5.02
					41.42 ± 1.07	100.61 ± 5.02
					35.49 ± 0.95	72.52 ± 4.40
Channel: 2mu2nu						
Sample	Data	H	$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet
All	–	138.42 ± 1.14	7429316.50 ± 2130.98	37318268.00 ± 15095.26	298977.34 ± 188.46	–
Vertex	–	138.41 ± 1.14	7426931.50 ± 2130.68	37298488.00 ± 15091.07	298975.12 ± 188.46	–
Jet cleaning	–	137.98 ± 1.14	7401038.00 ± 2127.45	37237056.00 ± 15079.59	298351.38 ± 188.25	–
Trigger	–	42.35 ± 0.63	1864790.00 ± 1134.22	6550383.50 ± 5916.42	77234.00 ± 92.20	–
2 leptons	–	24.66 ± 0.48	874448.81 ± 782.07	41.56 ± 5.89	2546.88 ± 12.99	–
$ m_{\ell\ell} - m_Z < 15$ GeV	811690	23.81 ± 0.47	799941.88 ± 748.41	11.80 ± 4.01	557.22 ± 6.07	0.00 ± 0.00
b -tagging cut	774697	21.43 ± 0.45	763444.81 ± 734.48	10.96 ± 3.98	55.25 ± 2.18	0.00 ± 0.00
E_t^{miss}	289	2.80 ± 0.13	155.85 ± 11.79	0.00 ± 0.00	25.59 ± 1.41	0.00 ± 0.00
$\Delta\phi_{ll}$ cuts	128	1.53 ± 0.10	42.71 ± 4.62	0.00 ± 0.00	17.53 ± 1.18	0.00 ± 0.00
$\Delta\phi(Z, E_t^{\text{miss}})$ cut	128	1.53 ± 0.10	42.71 ± 4.62	0.00 ± 0.00	17.53 ± 1.18	0.00 ± 0.00
$\Delta\phi(E_T^{\text{miss}}, jet)$ cut	96	1.36 ± 0.09	18.60 ± 3.50	0.00 ± 0.00	13.32 ± 1.05	0.00 ± 0.00
Total BG						
					22580.90 ± 67.71	–
					22578.22 ± 67.71	–
					22518.51 ± 67.62	–
					8011.32 ± 38.11	–
					1511.57 ± 12.41	–
					1046.86 ± 11.84	801557.75 ± 748.54
					781.28 ± 9.60	764292.25 ± 734.56
					76.06 ± 1.52	257.50 ± 11.97
					52.89 ± 1.22	113.13 ± 4.92
					52.89 ± 1.22	113.13 ± 4.92
					46.75 ± 1.16	78.67 ± 3.83

Table A.3: Cutoffs for the $H \rightarrow ZZ \rightarrow e^+e^-\nu\bar{\nu}$ (top) and $H \rightarrow ZZ \rightarrow \mu^+\mu^-\nu\bar{\nu}$ (bottom) channels for $m_H = 200$ GeV for the high pileup data period. The Monte Carlo H signal column only contains signal events in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay mode. Cross talk from other Higgs boson decay modes is not included in this table. The numbers for the data and data-driven multijet background are not reported before the 2 lepton requirement since the analysis is performed on a skimmed data sample which already has a dilepton requirement. The uncertainties shown are statistical only. Note that corrections to event weights to account for data MC differences in the selection efficiencies of leptons and the b -tagging are included at all stages.

Channel: 2c2nu								
Sample	Data	H	$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet	Diboson	totalBG
All	–	147.54 ± 1.12	7919042.50 ± 2033.35	39778216.00 ± 14020.96	318685.34 ± 183.42	–	24069.39 ± 66.63	–
Vertex	–	147.54 ± 1.12	7918842.00 ± 2033.32	39776628.00 ± 14020.68	318684.38 ± 183.42	–	24069.30 ± 66.63	–
Jet cleaning	–	147.28 ± 1.11	7894913.00 ± 2030.57	39721124.00 ± 14011.49	318130.78 ± 183.24	–	24017.02 ± 66.58	–
Trigger	–	46.40 ± 0.62	1809013.50 ± 1019.83	5978413.50 ± 5251.56	74855.16 ± 85.46	–	8398.09 ± 36.67	–
2 leptons	–	21.61 ± 0.42	722432.56 ± 647.79	428.62 ± 22.47	2426.48 ± 12.10	–	1359.57 ± 11.10	–
$ m_{\ell\ell} - m_Z < 15 \text{ GeV}$	680533	20.56 ± 0.41	660421.88 ± 620.25	88.52 ± 9.29	530.48 ± 5.70	2071.99 ± 8.87	942.30 ± 10.53	664055.19 ± 620.50
b -tagging cut	647779	18.59 ± 0.39	628967.12 ± 609.14	79.25 ± 8.85	61.41 ± 2.15	1910.41 ± 8.52	705.12 ± 8.55	631723.38 ± 609.33
E_T^{miss}	1029	2.85 ± 0.13	880.89 ± 24.05	7.36 ± 1.97	26.01 ± 1.35	3.34 ± 0.36	71.67 ± 1.39	989.27 ± 24.21
$\Delta\phi_{ll}$ cuts	307	1.64 ± 0.10	197.30 ± 10.28	6.54 ± 1.91	17.27 ± 1.03	1.67 ± 0.25	48.87 ± 1.13	271.66 ± 10.57
$\Delta\phi(lZ, E_T^{\text{miss}})$ cut	307	1.64 ± 0.10	197.30 ± 10.28	6.54 ± 1.91	17.27 ± 1.03	1.67 ± 0.25	48.87 ± 1.13	271.66 ± 10.57
$\Delta\phi(E_T^{\text{miss}}, \text{jet})$ cut	217	1.42 ± 0.09	124.20 ± 8.74	5.84 ± 1.84	12.73 ± 0.87	1.14 ± 0.21	43.06 ± 1.04	186.97 ± 9.04
Channel: 2mu2nu								
Sample	Data	H	$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet	Diboson	totalBG
All	–	147.54 ± 1.12	7919042.50 ± 2033.35	39778216.00 ± 14020.96	318685.34 ± 183.42	–	24069.39 ± 66.63	–
Vertex	–	147.54 ± 1.12	7918842.00 ± 2033.32	39776628.00 ± 14020.68	318684.38 ± 183.42	–	24069.30 ± 66.63	–
Jet cleaning	–	147.28 ± 1.11	7894913.00 ± 2030.57	39721124.00 ± 14011.49	318130.78 ± 183.24	–	24017.02 ± 66.58	–
Trigger	–	45.58 ± 0.61	1953586.50 ± 1058.23	6841977.00 ± 5723.62	81791.19 ± 89.18	–	8454.53 ± 36.68	–
2 leptons	–	25.84 ± 0.45	903503.12 ± 722.05	41.63 ± 4.62	2661.59 ± 12.35	–	1578.01 ± 11.80	–
$ m_{\ell\ell} - m_Z < 15 \text{ GeV}$	841699	24.78 ± 0.44	825531.69 ± 690.39	10.82 ± 2.02	590.87 ± 5.82	0.00 ± 0.00	1093.57 ± 11.24	827226.94 ± 690.51
b -tagging cut	802328	22.33 ± 0.42	787447.69 ± 678.04	9.96 ± 1.96	65.23 ± 2.10	0.00 ± 0.00	820.20 ± 9.21	788343.06 ± 678.11
E_T^{miss}	1359	3.57 ± 0.15	1226.50 ± 28.71	0.00 ± 0.00	30.13 ± 1.35	0.00 ± 0.00	85.68 ± 1.47	1342.31 ± 28.78
$\Delta\phi_{ll}$ cuts	341	2.03 ± 0.12	240.23 ± 11.21	0.00 ± 0.00	21.00 ± 1.09	0.00 ± 0.00	59.02 ± 1.22	320.25 ± 11.33
$\Delta\phi(lZ, E_T^{\text{miss}})$ cut	341	2.03 ± 0.12	240.23 ± 11.21	0.00 ± 0.00	21.00 ± 1.09	0.00 ± 0.00	59.02 ± 1.22	320.25 ± 11.33
$\Delta\phi(E_T^{\text{miss}}, \text{jet})$ cut	225	1.79 ± 0.11	140.55 ± 9.24	0.00 ± 0.00	15.17 ± 0.93	0.00 ± 0.00	51.36 ± 1.09	207.02 ± 9.35

Table A.4: Cutoffs for the $H \rightarrow ZZ \rightarrow e^+e^- \nu\bar{\nu}$ (top) and $H \rightarrow ZZ \rightarrow \mu^+\mu^- \nu\bar{\nu}$ (bottom) channels for $m_H = 400$ GeV for the low pileup data period. The Monte Carlo H signal column only contains signal events in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu\bar{\nu}$ decay mode. Cross talk from other Higgs boson decay modes is not included in this table. The numbers for the data and data-driven multijet background are not reported before the 2 lepton requirement since the analysis is performed on a skimmed data sample which already has a dilepton requirement. The uncertainties shown are statistical only. Note that corrections to event weights to account for data MC differences in the selection efficiencies of leptons and the b -tagging are included at all stages.

Sample	Data	H	Channel: 2e2nu				
			$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet	Diboson
All	–	54.29 ± 0.46	7429316.50 ± 2130.98	37318268.00 ± 15095.26	298977.34 ± 188.46	–	22580.90 ± 67.71
Vertex	–	54.29 ± 0.46	7426931.50 ± 2130.68	37298488.00 ± 15091.07	298975.12 ± 188.46	–	22578.22 ± 67.71
Jet cleaning	–	54.01 ± 0.46	7401038.00 ± 2127.45	37237056.00 ± 15079.59	298351.38 ± 188.25	–	22518.51 ± 67.62
Trigger	–	20.02 ± 0.28	1793964.62 ± 1085.92	6194778.50 ± 6014.80	73696.33 ± 90.15	–	8349.08 ± 38.50
2 leptons	–	10.69 ± 0.20	685885.69 ± 676.48	360.57 ± 20.63	2256.90 ± 12.27	–	1286.06 ± 11.47
$ m_{\ell\ell} - m_Z < 15$ GeV	647677	10.06 ± 0.19	626262.88 ± 647.26	79.56 ± 8.78	506.34 ± 5.78	1962.94 ± 8.41	891.03 ± 10.88
b -tagging cut	617159	8.79 ± 0.18	596689.25 ± 635.92	72.01 ± 8.62	51.58 ± 2.05	1809.86 ± 8.07	658.49 ± 8.85
E_t^{miss}	69	7.73 ± 0.17	22.55 ± 3.23	3.49 ± 1.75	13.81 ± 0.94	0.43 ± 0.12	33.97 ± 0.94
$\Delta\phi_{ll}$ cuts	48	7.61 ± 0.17	16.07 ± 2.03	1.95 ± 0.82	8.35 ± 0.75	0.11 ± 0.06	28.20 ± 0.85
$\Delta\phi(Z, E_t^{\text{miss}})$ cut	40	7.56 ± 0.17	11.40 ± 1.73	1.50 ± 0.75	7.83 ± 0.69	0.11 ± 0.06	26.60 ± 0.82
$\Delta\phi(E_t^{\text{miss}}, jet)$ cut	28	6.90 ± 0.16	0.46 ± 0.23	1.50 ± 0.75	7.05 ± 0.66	0.07 ± 0.05	24.63 ± 0.78
total BG							
							629702.81 ± 647.49
							599281.19 ± 636.09
							74.25 ± 3.91
							54.69 ± 2.46
							47.43 ± 2.18
							33.71 ± 1.29

Sample	Data	H	Channel: 2mu2nu				
			$Z + \text{jets}$	$W + \text{jets}$	Top	Multijet	Diboson
All	–	54.29 ± 0.46	7429316.50 ± 2130.98	37318268.00 ± 15095.26	298977.34 ± 188.46	–	22580.90 ± 67.71
Vertex	–	54.29 ± 0.46	7426931.50 ± 2130.68	37298488.00 ± 15091.07	298975.12 ± 188.46	–	22578.22 ± 67.71
Jet cleaning	–	54.01 ± 0.46	7401038.00 ± 2127.45	37237056.00 ± 15079.59	298351.38 ± 188.25	–	22518.51 ± 67.62
Trigger	–	18.41 ± 0.26	1864790.00 ± 1134.22	6550383.50 ± 5916.42	77234.00 ± 92.20	–	8011.32 ± 38.11
2 leptons	–	10.59 ± 0.20	874448.81 ± 782.07	41.56 ± 5.89	2546.88 ± 12.99	–	1511.57 ± 12.41
$ m_{\ell\ell} - m_Z < 15$ GeV	811690	9.88 ± 0.19	799941.88 ± 748.41	11.80 ± 4.01	557.22 ± 6.07	0.00 ± 0.00	1046.86 ± 11.84
b -tagging cut	774697	8.56 ± 0.18	763444.81 ± 734.48	10.96 ± 3.98	55.25 ± 2.18	0.00 ± 0.00	781.28 ± 9.60
E_t^{miss}	95	7.53 ± 0.17	24.12 ± 2.96	0.00 ± 0.00	16.29 ± 1.14	0.00 ± 0.00	41.81 ± 1.08
$\Delta\phi_{ll}$ cuts	72	7.39 ± 0.17	14.28 ± 1.45	0.00 ± 0.00	10.57 ± 0.92	0.00 ± 0.00	34.00 ± 0.97
$\Delta\phi(Z, E_t^{\text{miss}})$ cut	62	7.34 ± 0.17	10.83 ± 1.30	0.00 ± 0.00	9.69 ± 0.89	0.00 ± 0.00	32.44 ± 0.95
$\Delta\phi(E_t^{\text{miss}}, jet)$ cut	49	6.66 ± 0.16	0.38 ± 0.23	0.00 ± 0.00	8.98 ± 0.86	0.00 ± 0.00	30.34 ± 0.92
total BG							
							801557.75 ± 748.54
							764292.25 ± 734.56
							82.23 ± 3.35
							58.85 ± 1.97
							52.96 ± 1.83
							39.70 ± 1.28

Table A.5: Cutoffs for the $H \rightarrow ZZ \rightarrow e^+e^-\nu\bar{\nu}$ (top) and $H \rightarrow ZZ \rightarrow \mu^+\mu^-\nu\bar{\nu}$ (bottom) channels for $m_H = 200$ GeV for the high pileup data period. The Monte Carlo H signal column only contains signal events in the $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay mode. Cross talk from other Higgs boson decay modes is not included in this table. The numbers for the data and data-driven multijet background are not reported before the 2 lepton requirement since the analysis is performed on a skimmed data sample which already has a dilepton requirement. The uncertainties shown are statistical only. Note that corrections to event weights to account for data MC differences in the selection efficiencies of leptons and the b-tagging are included at all stages.

Channel: 2e2nu									
Sample	Data	H	Z + jets	W + jets	Top	Multijet	Diboson	total BG	
All	–	57.87 ± 0.45	7919042.50 ± 2033.35	39778216.00 ± 14020.96	318685.34 ± 183.42	–	24069.39 ± 66.63	–	
Vertex	–	57.87 ± 0.45	7918842.00 ± 2033.32	39776628.00 ± 14020.68	318684.38 ± 183.42	–	24069.30 ± 66.63	–	
Jet cleaning	–	57.66 ± 0.45	7894913.00 ± 2030.57	39721124.00 ± 14011.49	318130.78 ± 183.24	–	24017.02 ± 66.58	–	
Trigger	–	20.87 ± 0.27	1809013.50 ± 1019.83	5978413.50 ± 5251.56	74855.16 ± 85.46	–	8398.09 ± 36.67	–	
2 leptons	–	11.51 ± 0.20	722432.56 ± 647.79	428.62 ± 22.47	2426.48 ± 12.10	–	1359.57 ± 11.10	–	
$ m_{\ell\ell} - m_Z < 15$ GeV	680533	10.70 ± 0.19	660421.88 ± 620.25	88.52 ± 9.29	530.48 ± 5.70	2071.99 ± 8.87	942.30 ± 10.53	664055.19 ± 620.50	
b-tagging cut	647779	9.18 ± 0.18	628967.12 ± 609.14	79.25 ± 8.85	61.41 ± 2.15	1910.41 ± 8.52	705.12 ± 8.55	631723.38 ± 609.33	
E_T^{miss}	174	8.15 ± 0.17	107.38 ± 7.64	2.99 ± 1.40	16.41 ± 1.10	0.46 ± 0.13	41.15 ± 1.01	168.38 ± 7.91	
$\Delta\phi_{ll}$ cuts	81	8.05 ± 0.17	36.42 ± 3.49	2.71 ± 1.37	9.50 ± 0.76	0.11 ± 0.07	33.53 ± 0.90	82.27 ± 3.93	
$\Delta\phi(Z, E_T^{\text{miss}})$ cut	67	7.99 ± 0.17	22.90 ± 2.74	2.22 ± 1.32	7.91 ± 0.69	0.11 ± 0.07	31.28 ± 0.85	64.43 ± 3.24	
$\Delta\phi(E_T^{\text{miss}}, jet)$ cut	50	7.31 ± 0.16	4.25 ± 1.47	2.22 ± 1.32	7.19 ± 0.66	0.08 ± 0.05	28.90 ± 0.79	42.64 ± 2.23	
Channel: 2mu2nu									
Sample	Data	H	Z + jets	W + jets	Top	Multijet	Diboson	total BG	
All	–	57.87 ± 0.45	7919042.50 ± 2033.35	39778216.00 ± 14020.96	318685.34 ± 183.42	–	24069.39 ± 66.63	–	
Vertex	–	57.87 ± 0.45	7918842.00 ± 2033.32	39776628.00 ± 14020.68	318684.38 ± 183.42	–	24069.30 ± 66.63	–	
Jet cleaning	–	57.66 ± 0.45	7894913.00 ± 2030.57	39721124.00 ± 14011.49	318130.78 ± 183.24	–	24017.02 ± 66.58	–	
Trigger	–	19.09 ± 0.26	1953586.50 ± 1058.23	6841977.00 ± 5723.62	81791.19 ± 89.18	–	8454.53 ± 36.68	–	
2 leptons	–	11.07 ± 0.19	903503.12 ± 722.05	41.63 ± 4.62	2661.59 ± 12.35	–	1578.01 ± 11.80	–	
$ m_{\ell\ell} - m_Z < 15$ GeV	841699	10.41 ± 0.19	825531.69 ± 690.39	10.82 ± 2.02	590.87 ± 5.82	0.00 ± 0.00	1093.57 ± 11.24	827226.94 ± 690.51	
b-tagging cut	802328	9.04 ± 0.18	787447.69 ± 678.04	9.96 ± 1.96	65.23 ± 2.10	0.00 ± 0.00	820.20 ± 9.21	788343.06 ± 678.11	
E_T^{miss}	224	8.00 ± 0.16	120.85 ± 8.14	0.00 ± 0.00	20.01 ± 1.10	0.00 ± 0.00	50.20 ± 1.08	191.06 ± 8.29	
$\Delta\phi_{ll}$ cuts	104	7.84 ± 0.16	34.79 ± 3.16	0.00 ± 0.00	12.13 ± 0.84	0.00 ± 0.00	39.89 ± 0.97	86.81 ± 3.41	
$\Delta\phi(Z, E_T^{\text{miss}})$ cut	89	7.80 ± 0.16	26.09 ± 2.68	0.00 ± 0.00	10.83 ± 0.79	0.00 ± 0.00	37.48 ± 0.90	74.40 ± 2.93	
$\Delta\phi(E_T^{\text{miss}}, jet)$ cut	59	7.10 ± 0.16	7.36 ± 1.50	0.00 ± 0.00	10.02 ± 0.76	0.00 ± 0.00	35.24 ± 0.87	52.63 ± 1.89	

A.4.3 Systematic uncertainties

- **Electron energy scale and smearing:** treated as correlated across all signal and background samples.
- **Muon energy scale and smearing:** treated as correlated across all signal and background samples.
- **Jet energy scale and smearing:** treated as correlated across all signal and background samples.
- **b-tagging efficiency:** treated as correlated across signal and background samples.
- **Electron efficiency:** treated as correlated across signal and background samples.
- **Muon efficiency:** treated as correlated across signal and background samples.
- **MC estimated normalisation errors:** treated as correlated between $H \rightarrow ZZ \rightarrow e^+ e^- \nu \bar{\nu}$ and $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$ channels.
- **Control region normalisation error:** treated as correlated between $H \rightarrow ZZ \rightarrow e^+ e^- \nu \bar{\nu}$ and $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$ channels.
- **Luminosity uncertainty:** treated as correlated across all signal and background samples.
- **Z shape:** treated as correlated between $H \rightarrow ZZ \rightarrow e^+ e^- \nu \bar{\nu}$ and $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$ channels.
- **ZZ shape:** treated as correlated between $H \rightarrow ZZ \rightarrow e^+ e^- \nu \bar{\nu}$ and $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu \bar{\nu}$ channels.

systematic	ggF sig.		VBF sig.		ZZ		WZ/WW		top		Z		W		multijets	
	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$	ee	$\mu\mu$
e eff.	norm	no	norm	no	norm	no	norm	no	no	no	no	no	no	no	no	no
e scale*	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	no	no	no	no
e smear*	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	no	no	no	no
μ eff.	no	norm	no	norm	no	norm	no	norm	no	no	no	no	no	no	no	no
μ scale*	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
μ ID smear*	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	no	no	no
μ MS smear*	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	no	no	no
b/c-tag eff.	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	no	no	no	no
light-tag eff.	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	no	no	no	no
jet scale*	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no
jet smear*	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no
shape alt.MC†	no	no	no	no	no	no	no	no	no	no	shape	shape	no	no	no	no
p_T^H reweight†	norm.	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Accep. MC model†	norm.	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
PDF‡	norm.	no	norm.	no	norm.	no	norm.	no	no	no	no	no	no	no	no	no
QCD scale‡	norm.	no	norm.	no	norm.	no	norm.	no	no	no	no	no	no	no	no	no
Add correction†	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
CR correction†	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
luminosity‡	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no	norm.	no

Table A.6: Systematic variations applied in the confidence level fits in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel. For the cases where systematic uncertainties estimations only impact normalization or shape, it is specified.

*: Vectorial correction on the $\vec{p}_T^{\text{miss}}$ value is applied.

†: Systematics only relevant to $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ channel

‡: Systematic uncertainties expected to be correlated between ATLAS and CMS.

A.5 $H \rightarrow ZZ \rightarrow 4\ell$ additional information

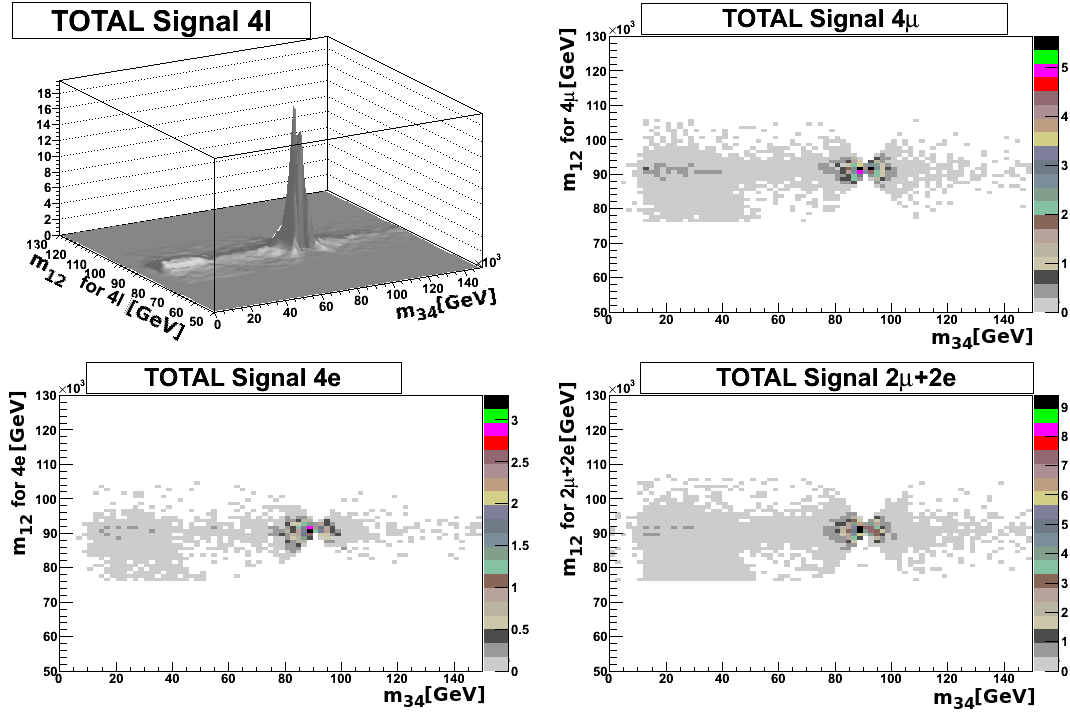


Figure A.24: m_{12} and m_{34} correlation plane of a Higgs boson signal of 200 GeV for the different subchannels. Top Left: all event candidates, Top Right: 4μ , Bottom Left: $4e$ and Bottom Right: $2\mu+2e$.

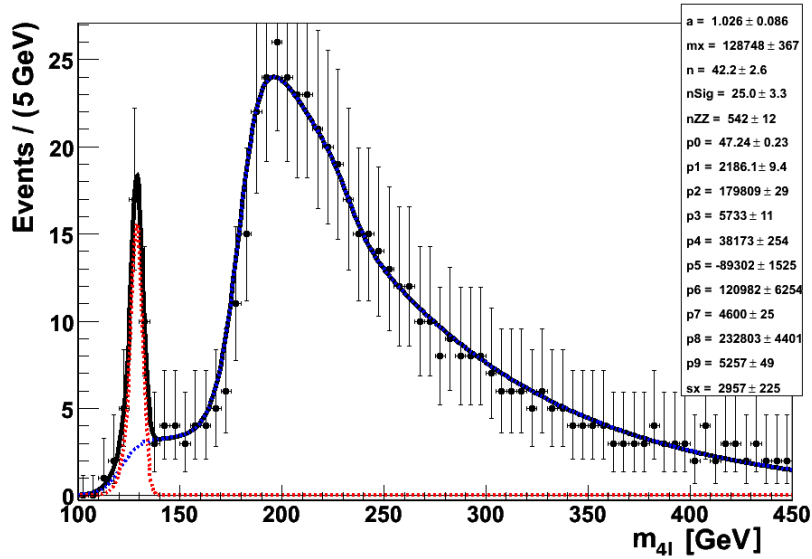


Figure A.25: Shapes of the fitted models fully composed simulated MC samples

Using the likelihood ratio semi-Bayesian formalism, exclusion limits were also estimated, see Fig. 6.7 right.

The sensitivity was also obtained through a fit formalism. Thousands of toy pseudoexperiments of the background only hypothesis and signal plus background hypotheses are generated. Then the likelihood of the distributions is calculated. The p -value is automatically obtained from the distribution given by the ratio of the likelihoods, and from this, p -value significances can be obtained using the expression:

$$S = \text{Erfc}^{-1} [2p - \text{value}] \sqrt{2} \quad (\text{A.3})$$

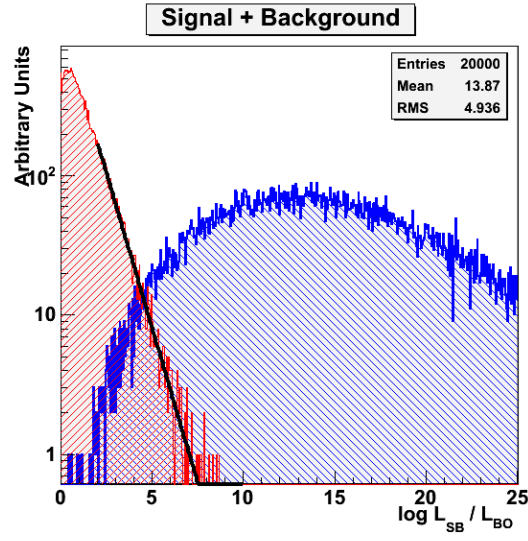


Figure A.26: Left: The distributions of the likelihood ratio for the toy MC pseudoexperiments for Background Only and Signal plus Background, Right: Comparison of sensitivity values obtained with number counting and using the fitting-Likelihood formalism.

A.6 $H \rightarrow WW$ additional information

A.6.1 Kinematic distributions and additional information

	signal (fb) <i>Signal</i>	background (fb)					
		WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	$di-jets$	<i>total</i>
before cuts	$6.7 \cdot 10^1$	$7.5 \cdot 10^3$	$2.5 \cdot 10^5$	$4.8 \cdot 10^7$	$4.7 \cdot 10^6$	$8.7 \cdot 10^6$	$6.2 \cdot 10^7$
L1 trigger	$6.6 \cdot 10^1$	$6.7 \cdot 10^3$	$2.4 \cdot 10^5$	$2.8 \cdot 10^7$	$3.7 \cdot 10^6$	$6.4 \cdot 10^6$	$3.9 \cdot 10^7$
L2 trigger	$6.3 \cdot 10^1$	$5.8 \cdot 10^3$	$1.8 \cdot 10^5$	$2.1 \cdot 10^7$	$3.0 \cdot 10^6$	$5.1 \cdot 10^6$	$2.9 \cdot 10^7$
event filter	$6.1 \cdot 10^1$	$5.4 \cdot 10^3$	$1.5 \cdot 10^5$	$1.9 \cdot 10^7$	$2.7 \cdot 10^6$	$4.8 \cdot 10^6$	$2.6 \cdot 10^7$

Table A.7: Trigger selection for the Weak Boson Fusion Higgs boson signal Monte Carlo sample ($m_H = 170$ GeV) and all relevant backgrounds. The $W + jets$ column includes contributions from WZ and Wbb . The $Z + jets$ column includes the ZZ and Zbb contributions. The $di-jets$ column includes the $b\bar{b}$ background. Cross-sections are given in fb.

Table A.8 summarizes the efficiencies of the lepton selection described above with respect to true² leptons with $p_T > 15$ GeV. These leptons are mainly from W decays; efficiencies are estimated based on the signal Monte Carlo sample (dataset ID: 109207($m_H = 170$ GeV)). Relative and cumulative selection efficiencies are shown.

cut	relative efficiency	cumulative efficiency
Muons $p_T > 15$ GeV		
reconstruction efficiency	0.93	0.93
pseudorapidity cuts	0.99	0.93
combined muon requirement	0.98	0.90
match χ^2 cut	0.997	0.90
d_0 significance cut	0.97	0.88
calorimeter isolation	0.95	0.83
track isolation	0.96	0.80
Electrons $p_T > 15$ GeV		
reconstruction efficiency	0.79	0.79
pseudorapidity cuts	0.96	0.76
standard “e-gamma”	0.97	0.73
“medium”	0.92	0.67
d_0 significance cut	0.91	0.61
calorimeter isolation	0.97	0.59
track isolation	0.96	0.57

Table A.8: Muon and electron reconstruction and selection efficiencies with respect to truth 15 GeV leptons.

For the estimation of the detector systematic uncertainties, the same ATLEAST-II samples were

²True leptons are electrons and muons generated by the original Monte Carlo generator, i.e. not GEANT4 particles from secondary interaction or decay products.

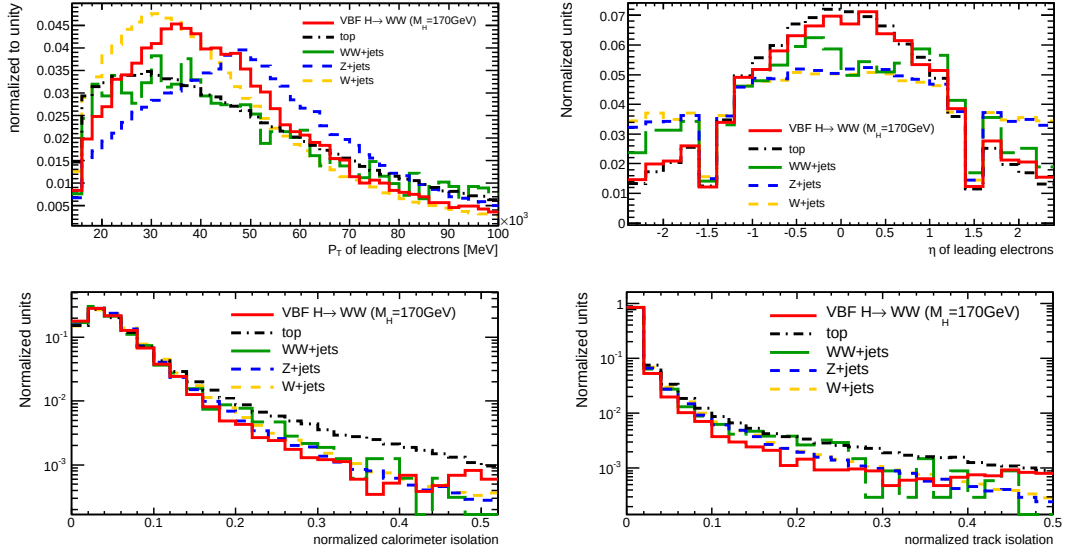


Figure A.27: Electron kinematics for signal and main backgrounds.

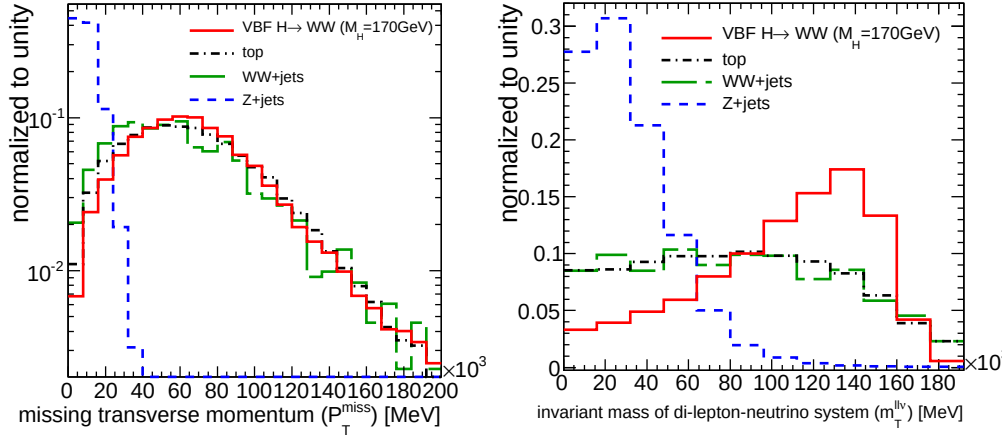


Figure A.28: Transverse momentum of the missing energy and di-lepton-neutrino system for signal and main backgrounds.

Appendix A. Appendix

used as for the Q^2 scale studies³. This was done in order to reduce the influence of limited MC statistics on the estimation of detector systematic uncertainties. A comparison between fast and full simulation is given in Table A.9, from which it is clear that the ATLFAST-II samples give much better precision. Small differences in details like electron efficiencies between ATLFAST-II and GEANT 4 can be expected to cancel out in the ratios, so only the effect of detector performance should contribute to the estimates of systematic uncertainty presented here.

Simulation	α_{top}	β_{top}	α_{WW}
ATLFAST-II	0.0201 ± 0.0011	0.2189 ± 0.0041	0.2315 ± 0.0095
relative error (%)	5	2	4
GEANT 4	0.0132 ± 0.0029	0.2349 ± 0.0135	0.1255 ± 0.0449
relative error (%)	22	6	36

Table A.9: Comparison between ATLFAST-II and GEANT 4 for the extrapolation ratios.

³Only central value samples were used.

A.7 $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0j$ additional information

A.7.1 Lepton Identification Studies

The most dangerous backgrounds in this channel come from processes like W +jets and $b\bar{b}$, which have very large cross-sections but which can be suppressed to a considerable degree by carefully chosen lepton identification and isolation cuts.

As mentioned in Sec. 6.1, the baseline electron selection algorithm in ATLAS is the IsEM algorithm, which is available in “Loose”, “Medium”, and “Tight” variants. Previous studies [27] have shown that this background is only manageable if a tight selection is used. As stated in the description on the analysis, muons are selected using the STACO algorithm; there is not presently an “IsEM-like” quality cut for muons.

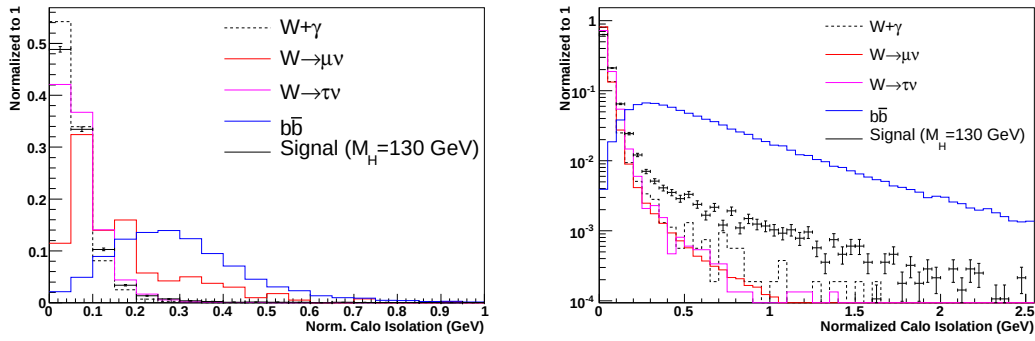


Figure A.29: Normalized calorimeter isolation in a cone of $\Delta R < 0.3$ for electrons (left) and muons (right).

Isolation cuts are crucial for suppressing backgrounds from heavy flavor decays. Leptons are required to be isolated by rejecting candidates where either the sum(P_T) of tracks or the sum of calorimeter depositions within a cone of a specified size is larger than some value; standard algorithms exist within ATLAS for cone sizes ranging from $\Delta R = 0.1$ to $\Delta R = 0.4$.⁴

Since leptons from b decays typically tend to be lower- P_T than leptons from the decays of on-shell W bosons, it makes sense to consider cutting on normalized isolation, i.e., the isolation energy or P_T divided by the P_T of the lepton candidates. Such a cut is tighter for low- P_T candidates than for high- P_T candidates. Figure A.29 shows example distributions for normalized calorimeter isolation using a cone size of $\Delta R = 0.3$, for electrons and muons. It is not immediately obvious whether or not it is actually better to cut on this variable than to cut on the flat isolation variable; it is necessary to study efficiency/rejection curves. Figure A.30

⁴The track isolation variables used for the plots in this Appendix are based on a private track isolation routine; the final “acceptance challenge” cuts are defined in terms of the TrackIsolationTool algorithm in Athena. There are a number of small differences between the two definitions; therefore the results presented here should only be taken as qualitative statements about the advantages of normalized isolation variables, and not as a detailed optimization study justifying the isolation cuts used elsewhere in the text.

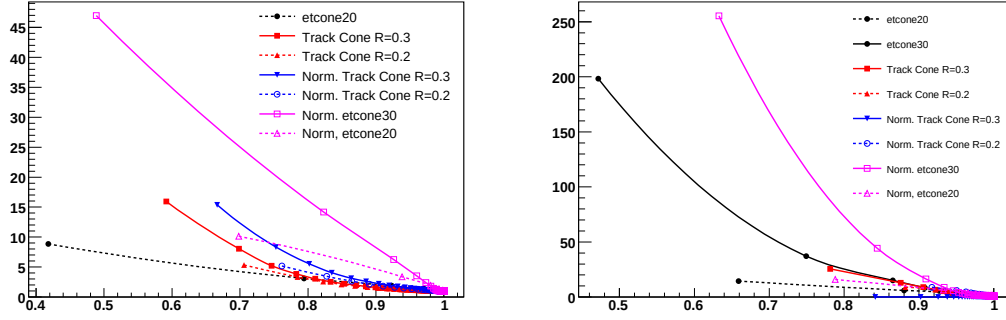


Figure A.30: Efficiency/rejection curves for various types of isolation for electrons (left) and muons (right).

shows these curves for normalized and unnormalized track and calorimeter isolation variables with various cone sizes, for both electrons and muons. The working point chosen for the analysis is normalized calorimeter isolation in a cone of $\Delta R = 0.3$ less than 0.2 and normalized track isolation in a cone of $\Delta R = 0.3$ less than 0.1, for both electrons and muons.

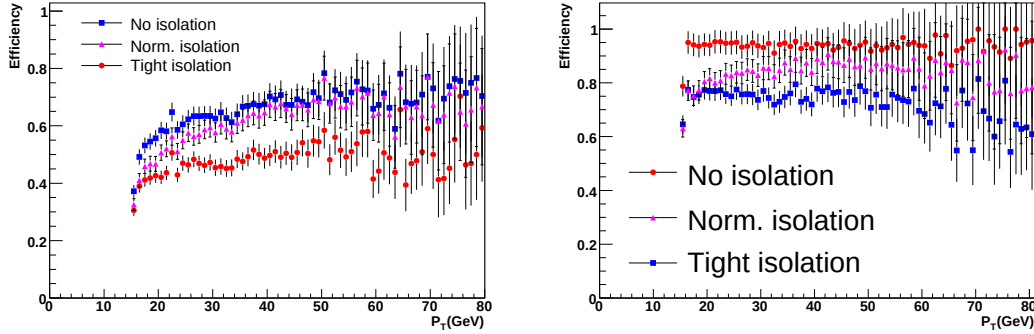


Figure A.31: Efficiency as a function of P_T for electrons (left) and muons (right).

The efficiency of the identification and isolation cuts is shown as a function of P_T and η for electrons and muons in Figure A.31. For reference, the efficiency curves are also shown with a tighter set of flat isolation cuts and without any isolation cuts applied. It is worth noting that, as expected, using the normalized isolation cuts instead of the flat isolation cuts increases the P_T dependency of the efficiency for both electrons and muons.

A.7.2 Flavor Tagging Studies

In any study of $H \rightarrow WW$ the top backgrounds, $t\bar{t}$ and single top, must be treated with care. These backgrounds include at least one b -jet in the final state, while there is no b -jet in the signal channel. The identification of b -jets can help to suppress the top background

contamination, and also provide a good method to define a b -tagged control sample as a data-driven method to estimate the top background contamination to the signal.

Many algorithms have been developed for b -tagging in ATLAS, but the most promising algorithms for early data are the simplest ones: TrackCounting, JetProb, SV0, and soft lepton taggers [27]. For this study, high b -tagging efficiency with acceptable light jet rejection is preferred in order to veto backgrounds with b -jets. Due to the low b -tagging efficiency expected from the soft lepton tagger, only the other three b -tagging algorithms are studied here. The TrackCounting algorithm tags a jet as a b -jet if the jet has at least some number of tracks (2 tracks for this study) with a large impact parameter. JetProb loops over the tracks in a jet, computes (for each track) the probability that a track produced at the primary vertex would have an impact parameter as large as the measured one, and takes the product of this probability for all tracks in a jet to produce a discriminating variable which can be used to select b -jets. SV0 exploits the secondary vertex information of B hadron decays, and identifies a b -jet by the significance of the signed distance between the secondary vertex and the primary vertex. All three of these b -tagging algorithms are recommended by ATLAS Flavor Tagging Working Group.

The performance of these b -taggers is studied first with $t\bar{t}$ events. Figure A.32 shows the curves of jet rejection versus b -tagging efficiency for the light jets (left plot) and the c -jets (right) for $t\bar{t}$ events. The b -tagging efficiency of SV0 can not go beyond 65% due to the limited reconstruction efficiency for the secondary vertices of b -jets. At high b -tagging efficiencies such as $\epsilon_b = 60\%$, the SV0 algorithm yields higher rejection for both light jets and c -jets, so SV0 is chosen for this study. The working point for a cut on the SV0 weight is chosen to give a b -tagging efficiency of 60%; the light jet rejection for this cut is 38. For $gg \rightarrow H \rightarrow WW$ and VBF $H \rightarrow WW$ signal events, the light jet rejection is 54 and 28 respectively. The differences among these light jet rejection figures arises from the different kinematic distributions of the jets in each channel. The above results are obtained using samples produced in release 14; a further study in release 15 also shows that SV0 has better performance when preferring a high b -tagging efficiency. However, it is worth mentioning that the rejection of light jets observed in release 15 is twice as large as that in release 14 due to technical changes in the taggers between releases.

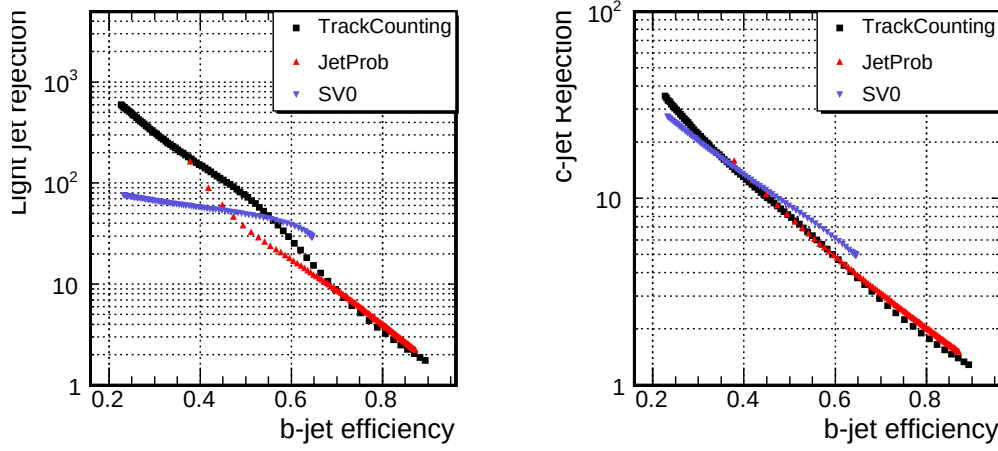


Figure A.32: Rejection of light jets and c -jets versus b -jet efficiency for $t\bar{t}$ events for all of three tagging algorithms: TrackCounting, JetProb, and SV0.

A.7.3 Optimization Studies

This Appendix describes a study of the optimization of the cuts on $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta\eta_{\ell\ell}$, P_T^{WW} , and P_T^{miss} . A simplified version of the analysis was developed using only the signal region and the main control region, and modeling the cross-sections for signal and background using a set of samples simulated with Atfast-I. In the optimization, only the signal, $qq \rightarrow WW$, $gg \rightarrow WW$, and $t\bar{t}$ backgrounds were considered, and only the $e\mu$ channel was studied.

Events were selected using the following cuts:

- Exactly two leptons with $P_T > 15$ GeV and $|\eta| < 2.5$
- No jets above 20 GeV in $|\eta| < 4.8$
- Reject events with a b -tagged jet having $P_T > 15$ GeV and $|\eta| < 2.5$, assuming a 60% b -tagging efficiency
- Reconstruct x_τ^1 and x_τ^2 using the collinear approximation; reject events where both are positive and $|m_{\tau\tau} - m_Z| < 25$ GeV
- Require $m_{\ell\ell} > 12$ GeV, $m_T^{\ell\ell\nu} > 30$ GeV, and $P_T^{\text{miss}} > 30$ GeV

After these preselection cuts, a signal region was defined by requiring $\Delta\phi_{\ell\ell} < \Delta\phi_{\ell\ell}^{\text{max}}$, $m_{\ell\ell} < m_{\ell\ell}^{\text{max}}$, $P_T^{\text{miss}} > P_T^{\text{miss}}(\text{min})$, $P_T^{WW} > P_T^{WW}(\text{min})$, $\Delta\eta_{\ell\ell} < \Delta\eta_{\ell\ell}^{\text{max}}$, and $m_T < m_H + 10$ GeV. Here, m_T is defined in the same way as in Ref. [136]; i.e, using the definition where the invariant mass of the neutrino-neutrino system is assumed to be the same as the dilepton invariant mass. Similarly, the control region is defined by selecting events where $\Delta\phi_{\ell\ell} > \Delta\phi_{\ell\ell}^{\text{max}}$, $m_{\ell\ell} > 80$ GeV,

$P_T^{\text{miss}} > P_T^{\text{miss}}(\text{min})$, and $P_T^{WW} > P_T^{WW}(\text{min})$; that is, reverse the $\Delta\phi_{\ell\ell}$ cut, reverse the $m_{\ell\ell}$ cut, drop the m_T and $\Delta\eta_{\ell\ell}$ cuts, and keep the P_T^{miss} and P_T^{WW} cuts the same. As in the analysis presented in Sec. 6.2, the control sample is used to normalize the continuum WW background ($qq \rightarrow WW$ plus $gg \rightarrow WW$) in the signal region; however, unlike the full analysis, the optimization study assumes that the small contamination from top is simply taken from Monte Carlo rather than measured in situ with additional control regions. The W +jets and $Z \rightarrow \tau\tau$ backgrounds are ignored completely. The purpose of these simplifications is to make the optimization more tractable.

The approximate significance for a given set of values of the parameters $\Delta\phi_{\ell\ell}^{\text{max}}$, $m_{\ell\ell}^{\text{max}}$, $P_T^{\text{miss}}(\text{min})$, $P_T^{WW}(\text{min})$, and $\Delta\eta_{\ell\ell}^{\text{max}}$ is given by $S/\sqrt{B + \Delta B^2}$, where S and B are the number of signal and background events (respectively) expected at 10 fb^{-1} , and ΔB is the uncertainty on the estimate of the background normalization based on the control sample. More specifically, ΔB is the sum in quadrature of the statistical error due to the finite number of events and the subtraction of the small contamination from top in the control sample plus the theoretical uncertainty on the extrapolation of the continuum WW background estimate from the control sample to the signal region. This uncertainty is recalculated for each value of the parameters considered during the optimization by running the selection for the signal region and control region on each of the Q^2 scale varied samples, computing the ratio of cross-sections in the two regions, and taking the largest fractional deviation from the central value to be the systematic error.

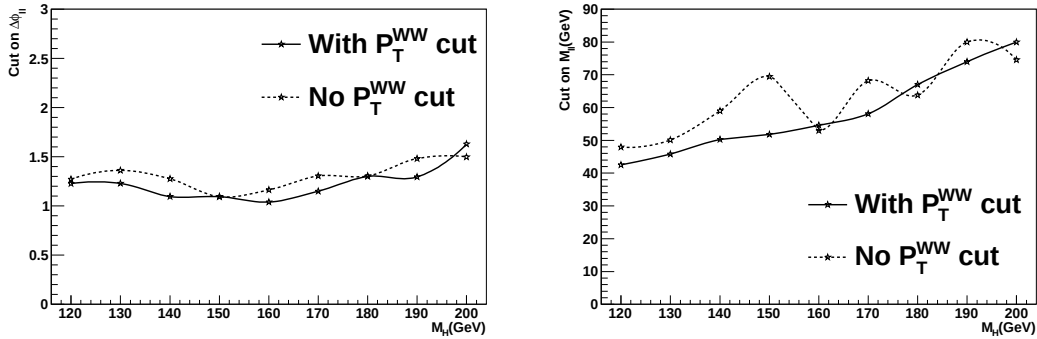


Figure A.33: The preferred values for $\Delta\phi_{\ell\ell}$ (left) and $m_{\ell\ell}$ (right) with (solid) and without (dashed) a cut on the P_T of the WW system considered in the optimization.

Using MINUIT, the approximate significance is maximized on the space of the parameters described above for Higgs boson mass hypotheses ranging from 120 GeV to 200 GeV. Figure A.33 shows, as examples, the best-fit values of the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ cuts as a function of the Higgs boson mass hypothesis. The plots show results from optimization runs with the $P_T^{WW}(\text{min})$ cut included and with this cut fixed to zero. (This was done because the P_T^{WW} cut does not appear to be very powerful.) For the same reason, plots of the optimal values of the $P_T^{\text{miss}}(\text{min})$ cut and the $\Delta\eta_{\ell\ell}$ cut are not shown. It is clear that the approximate significance is

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Working Point	$\Delta\phi_{\ell\ell}^{max}$	$m_{\ell\ell}^{max}$	$\Delta\eta_{\ell\ell}^{max}$	$P_T^{WW}(min)$	$P_T^{miss}(min)$	Uncert
A	1.5	50	-	-	30	3.8%
B	1.3	50	-	-	30	3.5%
C	1.5	50	-	10	30	8.3%
D	1.3	50	-	10	30	8.0%
E	1.5	50	-	-	50	6.9%
F	1.3	50	-	-	50	6.6%
G	1.2	50	-	-	30	4.4%
H	1.1	50	-	-	30	4.3%
I	1.0	50	-	-	30	5.0%
J	1.2	60	-	-	30	4.6%
K	1.0	60	1.0	-	30	6.2%

Table A.10: Values of cuts that were considered as possible working points in the optimization exercise.

largest if the $P_T^{miss}(min)$ cut is kept at 30 GeV. (This is the value applied during the preselection; lower values of this cut are not considered.) The wobbles are a consequence of the fact that the optimal value of the cut is not so strongly preferred over other values. In other words, the approximate significance would not be much lower if a slightly different value of the cut were chosen.

From the standpoint of simplicity, it is preferable to have a fixed set of cuts that does not depend on a Higgs boson mass hypothesis. In order to find such a set of cuts that maximizes the overall performance for the broadest mass range, a few working points have been tested and compared. The values of the various cuts are summarized in Table A.10; the table also shows an estimate of the systematic error on the extrapolation of the continuum WW background normalization from the control region to the signal region. This uncertainty estimate is taken to be the largest error for any value of the Higgs boson mass hypothesis, where the uncertainty for a particular mass hypothesis is computed as described in the previous paragraph. Figure A.34 shows the approximate significance as a function of m_H for the various working points considered. Overall, working point B seems to perform best for most masses; this is therefore the set of kinematic cuts chosen for the rest of the study.

The optimization discussed so far assumes that the central jet veto P_T threshold is set to 20 GeV. It is not obvious that this will be an appropriate value, especially in the early data. It is therefore important to have a rough idea to what extent the optimization depends on the choice of central jet veto P_T threshold. To this end, the optimization has been rerun with the jet veto P_T threshold set to several different values in the range of 20-35 GeV. Because the top background becomes more important as the jet veto P_T threshold is increased, a b -tagged control sample has been introduced to control its normalization in this part of the exercise. Events for the b -tagged control sample are selected from events that pass the preselection cuts by requiring $\Delta\phi_{\ell\ell} > \Delta\phi_{\ell\ell}^{max}$, $P_T^{miss} > P_T^{miss}(min)$, and $P_T^{WW} > P_T^{WW}(min)$, in addition

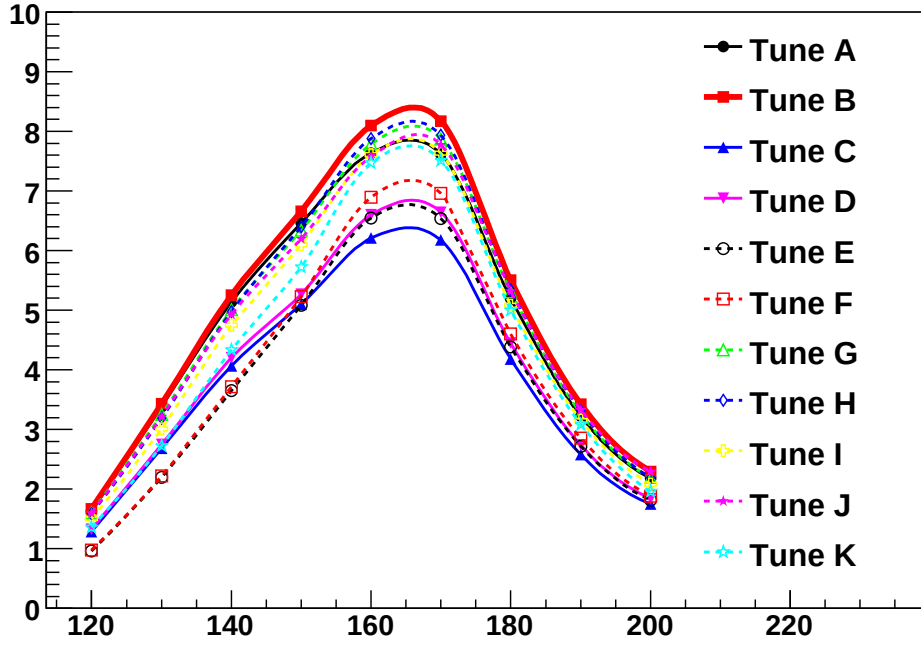


Figure A.34: The approximate significance as a function of Higgs boson mass for the various working points in Table A.10, with an integrated luminosity of 10 fb^{-1} .

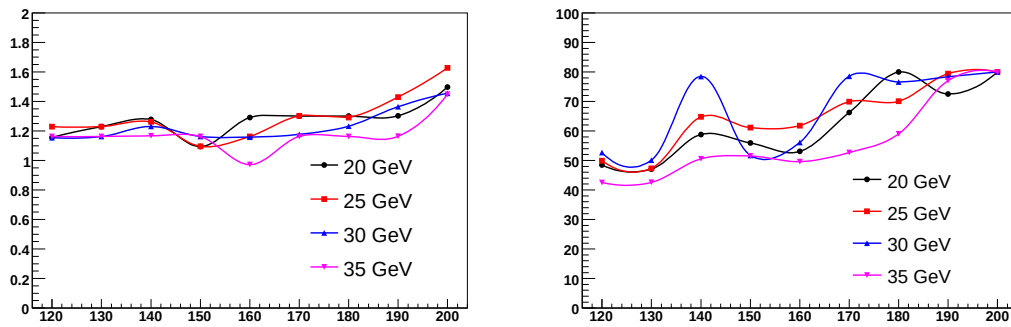


Figure A.35: The optimized values of $\Delta\phi_{\ell\ell}$ (left) and $m_{\ell\ell}$ (right) for several values of the jet veto P_T threshold.

to requiring that at least one jet is b -tagged. Based on the results presented in [103], a 9% theoretical uncertainty is assigned to the extrapolation from the b -tagged control region to the signal region. Figure A.35 shows the optimized values of the cuts on $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ for several choices of the jet veto P_T threshold. There is no significant difference among the curves for various thresholds, so it is unlikely that this optimization will need to be redone if the jet veto P_T threshold used in early data is not the same as the one used here.

A.7.4 Cutflows using Common Cuts

	Signal [fb]		Background [fb]				
	ggF	VBF	$WW + jets$	$t\bar{t} + Wt$	$W + jets$	$Z/\gamma^* + jets$	$total$
No Cuts	1550	201	33000	8.33×10^5	7.29×10^7	1.41×10^7	8.79×10^7
Weights	1400	201	23100	6.17×10^5	7.29×10^7	1.41×10^7	8.77×10^7
L1 Trigger	1340	198	20800	6.15×10^5	5.21×10^7	1.16×10^7	6.43×10^7
L2 Trigger	1300	189	18000	4.55×10^5	4.6×10^7	9.61×10^6	5.61×10^7
Event Filter	1250	183	16600	3.92×10^5	4.16×10^7	8.77×10^6	5.07×10^7
NonIsolated Lep	210	31.3	1450	18800	2990	7.6×10^5	7.84×10^5
Isolated Lep	187	27.8	1310	9010	169	7.11×10^5	7.22×10^5
Opposited Sign	187	27.8	1310	8900	169	7.11×10^5	7.21×10^5
Low DrellYan cut	175	26.1	1200	8160	104	1.25×10^5	1.34×10^5
Missing Pt	151	22.2	762	6600	49.2	394	7980
$m_T \ell\nu$	148	21	723	5800	49.2	164	6910
jet veto	77	2.91	409	59.4	29.5	47.4	625
$p_T^{\ell\ell} > 30$ GeV	74.9	2.72	374	54.2	23.3	17.8	547
$m_{ll} < 50$ GeV	48.2	1.85	99.3	7.96	6.43	0.65	164
$\Delta\phi_{ll} < 1.3$ rad	44.4	1.72	76.9	7.02	6.43	0.433	137
$m_T < m_H$	41.8	1.6	72	6.19	6.43	0.433	128

Table A.11: Signal region cross-sections cut-flow table using acceptance challenge cuts, adding the contributions of $e\mu$ $\mu\mu$ and ee .

	Signal Region	WW CR	W+jets CR	TopBox CR
Signal gg (170 GeV)	41.8	1.7	10.7	0.2
Signal VBF (170 GeV)	1.6	0.05	0.9	0.02
top	6.1	31.3	21.8	6550
WW	72.0	157.0	18.2	1.6
$W+jets$	6.4	2.0	409	816.1
$Z+jets$	0.4	10.2	10.1	37.8
$b\bar{b}$	< 4.1	< 4.1	< 4.1	< 4.1

Table A.12: Cross-sections (in fb) after Acceptance Challenge cuts, for different control regions adding the three different channels $e\mu$, ee and $\mu\mu$

This section documents the detailed cutflows using the common cuts (also referred to as the “acceptance challenge” cuts). Table A.11 shows the cutflows for this event selection, for a representative Higgs boson mass of 170 GeV. Table A.12 shows the corresponding cross-sections in the control regions. In both cases, the results are summed over lepton flavor.

A.7.5 Cutflow for the Aggressive and Conservative scenarios

This section documents the detailed cutflows for the aggressive and conservative scenarios. Tables A.13, A.14, and A.15 show the cutflows in the aggressive scenario, in the $e\mu$, $\mu\mu$, and ee channels, respectively. Tables A.16, A.17, and A.18 show the corresponding results for the conservative scenario. Table A.19 and Table A.20 show the cross-sections after all cuts in the aggressive scenario for various values of the Higgs boson mass at center-of-mass energies of 10 TeV and 7 TeV, respectively. Tables A.21 and A.22 show the corresponding results for the conservative scenario, and Table A.23 shows the results for the acceptance challenge cuts at a

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cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	18295	34.9%	31.2%
2 Good Non isolated leptons	13034	71.2%	22.3%
Exactly 2 opposite sign lep	10432	80%	17.8%
$m_{\ell\ell} > 15\text{ GeV}$	10052	96.4%	17.2%
p_T^{miss}	9038	89.9%	15.4%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	8895	98.4%	15.2%
$Z \rightarrow \tau\tau$ Rejection	8835	99.3%	15.1%
Central Jet Veto	4111	46.5%	7.02%
b -jet Veto	4101	99.8%	7%
$P_T^{\ell\ell} > 30\text{ GeV}$	3960	96.6%	6.76%
$m_{\ell\ell} < 50\text{ GeV}$	2484	62.7%	4.24%
Azimuthal Separation	2292	92.3%	3.91%
Transverse Mass Cut	2189	95.5%	3.74%

Table A.13: Cutflow table for the $e\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

center-of-mass energy of 10 TeV. Tables A.41 and A.44 show the cross-sections in the control samples for the aggressive scenario at 10 TeV and 7 TeV, respectively; Tables A.42 and A.45 show the corresponding results for the conservative scenario, and Table A.43 shows the results for the acceptance challenge cuts at 10 TeV.

A.7. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0j$ additional information

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	8713	16.6%	14.9%
2 Good Non isolated leptons	8713	100%	14.9%
Exactly 2 opposite sign lep	7906	90.7%	13.5%
$m_{\ell\ell} > 15\text{ GeV}$	7177	90.8%	12.3%
p_T^{miss}	5998	83.6%	10.2%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	5926	98.8%	10.1%
$Z \rightarrow \tau\tau$ Rejection	5911	99.7%	10.1%
Central Jet Veto	2634	44.6%	4.5%
b -jet Veto	2620	99.5%	4.47%
$P_T^{\ell\ell} > 30\text{ GeV}$	2586	98.7%	4.41%
$m_{\ell\ell} < 50\text{ GeV}$	1725	66.7%	2.94%
Azimuthal Separation	1594	92.4%	2.72%
Transverse Mass Cut	1459	91.5%	2.49%

Table A.14: Cutflow table for the $\mu\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	9942	19%	17%
2 Good Non isolated leptons	4545	45.7%	7.76%
Exactly 2 opposite sign lep	3526	77.6%	6.02%
$m_{\ell\ell} > 15\text{ GeV}$	3224	91.5%	5.5%
p_T^{miss}	2570	79.7%	4.39%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	2537	98.7%	4.33%
$Z \rightarrow \tau\tau$ Rejection	2526	99.6%	4.31%
Central Jet Veto	1157	45.8%	1.98%
b -jet Veto	1151	99.5%	1.97%
$P_T^{\ell\ell} > 30\text{ GeV}$	1135	98.6%	1.94%
$m_{\ell\ell} < 50\text{ GeV}$	757	66.7%	1.29%
Azimuthal Separation	685	90.5%	1.17%
Transverse Mass Cut	670	97.8%	1.14%

Table A.15: Cutflow table for the ee channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

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cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	18294	34.9%	31.2%
2 Good Non isolated leptons	13034	71.2%	22.3%
Exactly 2 opposite sign lep	11168	85.7%	19.1%
$m_{\ell\ell} > 15\text{ GeV}$	10753	96.3%	18.4%
p_T^{miss}	7474	69.5%	12.8%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	7403	99.1%	12.6%
$Z \rightarrow \tau\tau$ Rejection	7372	99.6%	12.6%
Central Jet Veto	4821	65.4%	8.23%
b -jet Veto	4795	99.5%	8.19%
$P_T^{\ell\ell} > 30\text{ GeV}$	4733	98.7%	8.08%
$m_{\ell\ell} < 50\text{ GeV}$	3156	66.7%	5.39%
Azimuthal Separation	2984	94.6%	5.09%
Transverse Mass Cut	2806	94%	4.79%

Table A.16: Cutflow table for the $e\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

A.7. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0j$ additional information

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	8707	16.6%	14.9%
2 Good Non isolated leptons	8707	100%	14.9%
Exactly 2 opposite sign lep	8081	92.8%	13.8%
$m_{\ell\ell} > 15\text{ GeV}$	7328	90.7%	12.5%
p_T^{miss}	5324	72.7%	9.09%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	5269	99%	9%
$Z \rightarrow \tau\tau$ Rejection	5259	99.8%	8.98%
Central Jet Veto	3369	64.1%	5.75%
b -jet Veto	3338	99.1%	5.7%
$P_T^{\ell\ell} > 30\text{ GeV}$	3309	99.1%	5.65%
$m_{\ell\ell} < 50\text{ GeV}$	2269	68.6%	3.87%
Azimuthal Separation	2136	94.1%	3.65%
Transverse Mass Cut	1936	90.6%	3.31%

Table A.17: Cutflow table for the $\mu\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	9932	19%	17%
2 Good Non isolated leptons	4536	45.7%	7.74%
Exactly 2 opposite sign lep	3955	87.2%	6.75%
$m_{\ell\ell} > 15\text{ GeV}$	3615	91.5%	6.17%
p_T^{miss}	2451	67.8%	4.18%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	2422	98.8%	4.13%
$Z \rightarrow \tau\tau$ Rejection	2411	99.5%	4.12%
Central Jet Veto	1545	64.1%	2.64%
b -jet Veto	1529	99%	2.61%
$P_T^{\ell\ell} > 30\text{ GeV}$	1512	98.9%	2.58%
$m_{\ell\ell} < 50\text{ GeV}$	1046	69.2%	1.79%
Azimuthal Separation	989	94.6%	1.69%
Transverse Mass Cut	958	96.9%	1.64%

Table A.18: Cutflow table for the ee channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

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$e\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	2.56	0.12	0.44	15.0	–	0.43
130	6.10	0.46	0.68	19.2	–	0.43
140	9.99	1.01	0.87	23.1	–	0.43
150	14.8	1.47	1.05	26.1	–	0.43
160	22.0	1.80	1.25	28.5	–	0.43
165	20.4	1.98	1.33	29.6	–	0.43
170	17.6	1.98	1.39	30.1	–	0.43
180	13.5	1.98	1.47	31.1	–	0.43
190	7.34	2.25	1.53	31.5	–	0.43
200	5.11	2.25	1.55	31.6	–	0.43
$\mu\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	1.49	0.06	0.21	10.0	4.15	–
130	4.07	0.06	0.36	13.9	4.15	–
140	7.01	0.32	0.52	17.1	4.15	–
150	10.2	0.58	0.70	19.6	4.15	–
160	13.4	0.83	0.85	21.4	4.15	–
165	13.5	0.96	0.92	22.1	4.15	–
170	11.7	0.96	0.98	22.5	4.15	–
180	7.60	1.14	1.06	23.4	4.15	–
190	5.74	1.14	1.09	23.8	4.15	–
200	3.54	1.14	1.09	24.3	4.15	–
ee Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.59	0.13	0.11	4.70	–	–
130	1.61	0.20	0.18	5.85	–	–
140	2.84	0.12	0.27	7.34	–	–
150	4.42	0.18	0.33	7.87	–	–
160	6.28	0.38	0.40	8.54	–	–
165	6.28	0.38	0.42	8.64	–	–
170	5.40	0.45	0.44	8.83	–	–
180	4.30	0.45	0.47	9.21	–	–
190	2.62	0.45	0.48	9.40	–	–
200	1.33	0.45	0.48	9.40	–	–

Table A.19: Cross-sections after cuts in the signal region, for various Higgs boson masses and a center-of-mass energy of 10 TeV, using the cuts defined for the aggressive scenario.

A.7. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0j$ additional information

$e\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	1.36	0.06	0.22	10.3	–	0.31
130	3.19	0.20	0.33	13.2	–	0.31
140	5.15	0.51	0.43	15.9	–	0.31
150	7.57	0.69	0.52	18.0	–	0.31
160	11.0	0.82	0.62	19.6	–	0.31
165	10.1	0.90	0.65	20.4	–	0.31
170	8.70	0.90	0.68	20.7	–	0.31
180	6.61	0.90	0.72	21.4	–	0.31
190	3.44	0.99	0.75	21.7	–	0.31
200	2.43	0.99	0.76	21.8	–	0.31
$\mu\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.78	0.03	0.10	6.86	3.08	–
130	2.11	0.03	0.17	9.57	3.08	–
140	3.58	0.10	0.25	11.8	3.08	–
150	5.21	0.24	0.33	13.7	3.08	–
160	6.65	0.33	0.41	15.0	3.08	–
165	6.60	0.39	0.44	15.5	3.08	–
170	5.70	0.39	0.47	15.8	3.08	–
180	3.65	0.46	0.51	16.4	3.08	–
190	2.74	0.46	0.52	16.7	3.08	–
200	1.67	0.46	0.52	17.1	3.08	–
ee Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.32	0.06	0.06	3.21	–	–
130	0.85	0.08	0.09	3.91	–	–
140	1.48	0.06	0.13	4.90	–	–
150	2.26	0.09	0.17	5.25	–	–
160	3.13	0.17	0.20	5.68	–	–
165	3.13	0.17	0.21	5.73	–	–
170	2.69	0.20	0.22	5.87	–	–
180	2.12	0.20	0.23	6.12	–	–
190	1.25	0.20	0.24	6.25	–	–
200	0.65	0.20	0.24	6.25	–	–

Table A.20: Cross-sections after cuts in the signal region, for various Higgs boson masses and a center-of-mass energy of 7 TeV, using the cuts defined for the aggressive scenario.

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<i>eμ</i> Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	1.36	0.48	0.28	6.51	2.28	–
130	4.74	0.74	0.59	11.4	2.27	–
140	9.89	1.95	0.87	16.4	2.27	–
150	15.9	2.74	1.17	20.4	2.27	–
160	27.0	3.67	1.47	23.6	2.27	–
165	26.8	4.05	1.57	24.8	2.27	–
170	22.9	4.18	1.68	25.3	2.27	–
180	18.2	4.85	1.79	26.4	2.27	–
190	10.1	5.18	1.87	27.0	2.27	–
200	6.92	5.24	1.91	27.3	2.27	–
$\mu\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	1.13	0.39	0.16	6.66	–	–
130	3.70	0.57	0.35	11.5	–	–
140	7.52	1.17	0.57	15.0	–	–
150	11.8	2.53	0.82	17.8	–	–
160	18.7	3.04	1.03	20.0	–	–
165	17.9	3.36	1.12	21.0	–	–
170	15.8	3.70	1.19	21.7	–	–
180	10.5	4.09	1.30	22.9	–	–
190	7.55	4.29	1.35	23.4	–	–
200	4.70	4.62	1.36	24.0	–	–
<i>ee</i> Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.36	0.20	0.08	2.93	–	–
130	1.39	0.26	0.18	4.46	–	–
140	3.03	0.66	0.31	6.43	–	–
150	5.84	0.97	0.42	7.39	–	–
160	7.85	1.44	0.51	8.45	–	–
165	9.12	1.44	0.54	8.64	–	–
170	7.82	1.50	0.57	8.83	–	–
180	5.59	1.70	0.61	9.36	–	–
190	4.03	1.56	0.62	9.65	–	–
200	2.09	1.56	0.63	9.65	–	–

Table A.21: Cross-sections after cuts in the signal region, for various Higgs boson masses and a center-of-mass energy of 10 TeV, using the cuts defined for the conservative scenario.

A.7. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0j$ additional information

$e\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.72	0.18	0.14	4.59	1.85	–
130	2.48	0.29	0.29	7.90	1.85	–
140	5.11	0.92	0.43	11.3	1.85	–
150	8.05	1.18	0.57	14.2	1.85	–
160	13.5	1.56	0.72	16.3	1.85	–
165	13.3	1.72	0.77	17.2	1.85	–
170	11.3	1.77	0.82	17.5	1.85	–
180	8.88	2.12	0.87	18.3	1.85	–
190	4.82	2.24	0.91	18.7	1.85	–
200	3.29	2.26	0.93	18.9	1.85	–

$\mu\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.59	0.09	0.08	4.59	–	–
130	1.92	0.16	0.17	7.84	–	–
140	3.84	0.45	0.27	10.4	–	–
150	5.92	0.95	0.39	12.4	–	–
160	9.35	1.19	0.49	14.0	–	–
165	8.77	1.32	0.54	14.7	–	–
170	7.68	1.47	0.57	15.2	–	–
180	4.98	1.66	0.62	16.0	–	–
190	3.59	1.69	0.64	16.4	–	–
200	2.21	1.83	0.65	16.8	–	–

ee Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.19	0.09	0.04	2.02	–	–
130	0.73	0.13	0.09	2.94	–	–
140	1.57	0.35	0.16	4.28	–	–
150	2.98	0.47	0.21	4.94	–	–
160	3.92	0.68	0.25	5.58	–	–
165	4.56	0.68	0.27	5.69	–	–
170	3.90	0.70	0.28	5.84	–	–
180	2.75	0.79	0.30	6.19	–	–
190	1.90	0.73	0.30	6.39	–	–
200	1.02	0.73	0.31	6.39	–	–

Table A.22: Cross-sections after cuts in the signal region, for various Higgs boson masses and a center-of-mass energy of 7 TeV, using the cuts defined for the conservative scenario.

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<i>eμ</i> Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	3.05	0.66	0.60	16.5	2.28	0.43
130	7.32	1.20	0.89	21.1	2.28	0.43
140	12.3	1.99	1.13	25.6	2.28	0.43
150	18.0	2.71	1.37	29.0	2.28	0.43
160	27.0	3.16	1.64	31.6	2.28	0.43
165	25.5	3.41	1.73	32.8	2.28	0.43
170	21.9	3.61	1.83	33.4	2.28	0.43
180	17.1	3.75	1.92	34.5	2.28	0.43
190	9.81	4.01	1.99	35.0	2.28	0.43
200	6.47	4.01	2.03	35.1	2.28	0.43
$\mu\mu$ Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	1.70	0.12	0.28	10.7	4.16	–
130	4.63	0.32	0.46	15.2	4.16	–
140	8.08	0.65	0.65	18.5	4.16	–
150	10.8	1.11	0.88	21.1	4.16	–
160	15.6	1.56	1.06	23.0	4.16	–
165	16.2	1.75	1.14	23.8	4.16	–
170	14.3	1.75	1.20	24.4	4.16	–
180	8.92	1.93	1.29	25.4	4.16	–
190	6.58	1.99	1.32	25.8	4.16	–
200	4.25	2.13	1.33	26.4	4.16	–
<i>ee</i> Channel:						
m_H [GeV]	Signal [fb]	top [fb]	gg WW [fb]	qq WW [fb]	$W+X$ [fb]	$Z+X$ [fb]
120	0.74	0.14	0.14	5.47	–	–
130	2.04	0.26	0.23	6.91	–	–
140	3.72	0.25	0.34	8.59	–	–
150	5.90	0.37	0.42	9.46	–	–
160	8.01	0.57	0.51	10.3	–	–
165	8.60	0.63	0.54	10.4	–	–
170	7.14	0.83	0.56	10.6	–	–
180	5.33	0.90	0.60	11.0	–	–
190	3.80	0.90	0.61	11.2	–	–
200	1.93	0.96	0.62	11.2	–	–

Table A.23: Cross-sections after cuts in the signal region, for various Higgs boson masses and a center-of-mass energy of 10 TeV, using the cuts defined for the acceptance challenge.

A.7. $H \rightarrow WW \rightarrow \ell \nu \ell \nu + 0j$ additional information

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	Top box
Signal($m_H = 120$ GeV)	–	–	–	1.12	N/A
Signal($m_H = 130$ GeV)	0.03	–	–	2.50	N/A
Signal($m_H = 140$ GeV)	0.30	0.01	0.02	4.24	N/A
Signal($m_H = 150$ GeV)	0.80	–	–	5.12	N/A
Signal($m_H = 160$ GeV)	0.89	–	0.11	8.37	N/A
Signal($m_H = 165$ GeV)	0.91	0.04	0.07	7.97	N/A
Signal($m_H = 170$ GeV)	1.24	0.03	0.16	6.88	N/A
Signal($m_H = 180$ GeV)	2.81	0.09	0.27	4.57	N/A
Signal($m_H = 190$ GeV)	4.00	0.27	0.68	3.01	N/A
Signal($m_H = 200$ GeV)	3.90	0.54	1.26	2.02	N/A
$t\bar{t}$	11.9	3.51	4.05	12.2	6978
$gg \rightarrow WW$	2.22	0.39	0.83	0.74	N/A
$qq \rightarrow WW$	80.1	17.0	34.5	10.6	N/A
W +jets	2.08	–	–	307	935.3
Z +jets	1.13	1.13	3.73	8.06	42.62

Table A.24: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the aggressive scenario.

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	Top box
Signal($m_H = 120$ GeV)	0.00	–	–	0.58	N/A
Signal($m_H = 130$ GeV)	0.02	–	0.00	1.28	N/A
Signal($m_H = 140$ GeV)	0.15	0.01	0.01	2.15	N/A
Signal($m_H = 150$ GeV)	0.41	–	–	2.53	N/A
Signal($m_H = 160$ GeV)	0.46	–	0.04	4.17	N/A
Signal($m_H = 165$ GeV)	0.44	0.02	0.04	3.87	N/A
Signal($m_H = 170$ GeV)	0.61	0.02	0.08	3.33	N/A
Signal($m_H = 180$ GeV)	1.32	0.05	0.14	2.16	N/A
Signal($m_H = 190$ GeV)	1.94	0.13	0.32	1.46	N/A
Signal($m_H = 200$ GeV)	1.86	0.26	0.60	0.93	N/A
$t\bar{t}$	4.78	1.28	1.55	4.46	2475
$gg \rightarrow WW$	1.01	0.17	0.37	0.35	N/A
$qq \rightarrow WW$	52.7	11.2	22.7	7.13	N/A
W +jets	1.54	–	–	223	373.8
Z +jets	0.80	0.65	2.14	5.66	14.01

Table A.25: Cross-sections after cuts in the various control regions for a center-of-mass energy of 7 TeV, using the cuts defined for the aggressive scenario.

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Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	Top box
Signal($m_H = 120$ GeV)	–	–	–	0.56	N/A
Signal($m_H = 130$ GeV)	0.001	–	–	1.62	N/A
Signal($m_H = 140$ GeV)	0.02	–	0.01	3.23	N/A
Signal($m_H = 150$ GeV)	–	–	–	4.02	N/A
Signal($m_H = 160$ GeV)	0.33	–	–	8.62	N/A
Signal($m_H = 165$ GeV)	0.43	0.03	0.04	8.11	N/A
Signal($m_H = 170$ GeV)	0.77	0.02	0.09	6.66	N/A
Signal($m_H = 180$ GeV)	2.41	0.18	0.36	4.29	N/A
Signal($m_H = 190$ GeV)	3.41	0.21	0.35	3.27	N/A
Signal($m_H = 200$ GeV)	4.26	0.57	1.24	1.92	N/A
$t\bar{t}$	27.7	7.76	12.4	10.7	4530
$gg \rightarrow WW$	2.14	0.54	0.99	0.67	N/A
$qq \rightarrow WW$	54.4	14.6	30.2	8.61	N/A
W +jets	–	–	–	105	414.3
Z +jets	1.35	1.13	3.95	1.3	22.48

Table A.26: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the conservative scenario.

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	Top box
Signal($m_H = 120$ GeV)	–	–	–	0.29	N/A
Signal($m_H = 130$ GeV)	0.00	–	–	0.83	N/A
Signal($m_H = 140$ GeV)	0.01	–	0.00	1.64	N/A
Signal($m_H = 150$ GeV)	0.03	–	–	2.01	N/A
Signal($m_H = 160$ GeV)	0.16	–	–	4.29	N/A
Signal($m_H = 165$ GeV)	0.21	0.01	0.02	3.93	N/A
Signal($m_H = 170$ GeV)	0.38	0.01	0.04	3.22	N/A
Signal($m_H = 180$ GeV)	1.12	0.09	0.18	2.07	N/A
Signal($m_H = 190$ GeV)	1.65	0.10	0.18	1.59	N/A
Signal($m_H = 200$ GeV)	2.02	0.27	0.59	0.88	N/A
$t\bar{t}$	10.9	2.93	4.71	4.15	1608
$gg \rightarrow WW$	0.95	0.23	0.43	0.32	N/A
$qq \rightarrow WW$	35.0	9.43	19.6	5.83	N/A
W +jets	–	–	–	76.5	160.3
Z +jets	0.96	0.65	2.40	0.90	7.48

Table A.27: Cross-sections after cuts in the various control regions for a center-of-mass energy of 7 TeV, using the cuts defined for the conservative scenario.

A.7. $H \rightarrow WW \rightarrow \ell \nu \ell \nu + 0j$ additional information

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	Top box
Signal($m_H = 120$ GeV)	0.002	–	–	1.31	N/A
Signal($m_H = 130$ GeV)	0.04	–	–	2.91	N/A
Signal($m_H = 140$ GeV)	0.33	0.01	0.02	4.92	N/A
Signal($m_H = 150$ GeV)	1.01	–	–	5.86	N/A
Signal($m_H = 160$ GeV)	1.03	–	0.11	10.1	N/A
Signal($m_H = 165$ GeV)	1.13	0.05	0.08	9.49	N/A
Signal($m_H = 170$ GeV)	1.56	0.03	0.18	8.09	N/A
Signal($m_H = 180$ GeV)	3.68	0.18	0.30	5.39	N/A
Signal($m_H = 190$ GeV)	4.86	0.55	0.70	3.63	N/A
Signal($m_H = 200$ GeV)	5.21	0.69	1.46	2.37	N/A
$t\bar{t}$	17.5	5.45	8.30	15.7	6549
$gg \rightarrow WW$	2.86	0.53	1.01	0.89	N/A
$qq \rightarrow WW$	93.6	19.9	39.1	12.3	N/A
W +jets	2.08	–	–	317	816.2
Z +jets	1.35	1.13	7.68	8.28	37.77

Table A.28: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the acceptance challenge.

A.8 $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

This appendix documents several tables which provide additional information with respect to what appears in the main body of the text. Table A.29 shows the cutflow for signal and background using the acceptance challenge cuts. Tables A.30 through A.35 show the sum of the event weights, the relative efficiencies, and the cumulative efficiencies, for the Monte Carlo events remaining after each cut for a signal Monte Carlo sample, using the cuts for the aggressive and conservative scenarios, Tables A.36 through A.40 show the cross-sections remaining in the signal region for the signal and background for each of the Higgs boson masses considered, at 7 and 10 TeV, for the cuts of the aggressive scenario, the conservative scenario, and the acceptance challenge. Tables A.41 through A.45 show the cross-sections after all cuts in each of the control regions, for the various center-of-mass energies and cut scenarios considered.

A.8.1 Cutflow using Common Cuts

	Signal [fb]		Background [fb]				
	ggH	VBF	WW +jets	$t\bar{t} + Wt$	W +jets	$Z/\gamma^* + \text{jets}$	total
Exactly 2Lep	187	27.8	1310	8880	249	8.55×10^5	8.65×10^5
Low DrellYan	175	26.1	1200	8160	207	1.15×10^5	1.25×10^5
Missing Pt	151	22.2	762	6600	74.2	620	8230
$m_T \ell\nu$	148	21	723	5800	73.2	216	6980
jet tagging	71.5	18.1	314	5740	40.6	182	6370
jet acceptance	50.5	9.81	207	704	27.8	60.3	1060
b-jet veto	48.9	9.31	199	316	27.8	51.8	653
$p_T^{tot} < 30$ GeV	40.9	4.37	174	200	26.4	36.5	482
$Z \rightarrow \tau\tau$ rejection	40.7	4.31	166	188	23.2	16.6	439
$m_{ll} < 50$ GeV	25.8	2.71	39.2	36.2	5.32	11.2	120
$\Delta\phi_{ll} < 1.3$ rad	23.1	2.42	27.6	29.8	3.21	2.76	88.9
$m_T < m_H$	21.5	2.26	25.5	25.9	3.21	2.76	81.1

Table A.29: Signal region cross-sections cut-flow table using acceptance challenge cuts, adding the contributions of $e\mu\mu\mu$ and ee .

A.8.2 Cutflow for Aggressive and Conservative Scenarios

A.8. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	18295	34.9%	31.2%
2 Good Non isolated leptons	13034	71.2%	22.3%
Exactly 2 opposite sign lep	10432	80%	17.8%
$m_{\ell\ell} > 15\text{ GeV}$	10052	96.4%	17.2%
p_T^{miss}	9038	89.9%	15.4%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	8895	98.4%	15.2%
Jet Tagging	4779	53.7%	8.16%
Central Jet Veto	3136	65.6%	5.35%
b -jet Veto	3056	97.4%	5.22%
$P_T^{\ell\ell} > 30\text{ GeV}$	2782	91%	4.75%
$Z \rightarrow \tau\tau$ Rejection	2761	99.2%	4.71%
$m_{\ell\ell} < 50\text{ GeV}$	1675	60.7%	2.86%
Azimuthal Separation	1474	88%	2.52%
Transverse Mass Cut	1383	93.8%	2.36%

Table A.30: Cutflow table for the $e\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	8713	16.6%	14.9%
2 Good Non isolated leptons	8713	100%	14.9%
Exactly 2 opposite sign lep	7906	90.7%	13.5%
$m_{\ell\ell} > 15\text{ GeV}$	7177	90.8%	12.3%
p_T^{miss}	5998	83.6%	10.2%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	5926	98.8%	10.1%
Jet Tagging	3291	55.5%	5.62%
Central Jet Veto	2224	67.6%	3.8%
b -jet Veto	2161	97.2%	3.69%
$P_T^{\ell\ell} > 30\text{ GeV}$	1961	90.7%	3.35%
$Z \rightarrow \tau\tau$ Rejection	1956	99.7%	3.34%
$m_{\ell\ell} < 50\text{ GeV}$	1318	67.4%	2.25%
Azimuthal Separation	1193	90.5%	2.04%
Transverse Mass Cut	1079	90.4%	1.84%

Table A.31: Cutflow table for the $\mu\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

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cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	9942	19%	17%
2 Good Non isolated leptons	4545	45.7%	7.76%
Exactly 2 opposite sign lep	3526	77.6%	6.02%
$m_{\ell\ell} > 15\text{ GeV}$	3224	91.5%	5.5%
p_T^{miss}	2570	79.7%	4.39%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	2537	98.7%	4.33%
Jet Tagging	1380	54.4%	2.36%
Central Jet Veto	900	65.2%	1.54%
b -jet Veto	874	97.1%	1.49%
$P_T^{\ell\ell} > 30\text{ GeV}$	799	91.4%	1.36%
$Z \rightarrow \tau\tau$ Rejection	797	99.7%	1.36%
$m_{\ell\ell} < 50\text{ GeV}$	508	63.7%	0.867%
Azimuthal Separation	453	89.2%	0.773%
Transverse Mass Cut	438	96.7%	0.748%

Table A.32: Cutflow table for the ee channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the aggressive scenario

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	18294	34.9%	31.2%
2 Good Non isolated leptons	13034	71.2%	22.3%
Exactly 2 opposite sign lep	11168	85.7%	19.1%
$m_{\ell\ell} > 15\text{ GeV}$	10753	96.3%	18.4%
p_T^{miss}	7474	69.5%	12.8%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	7403	99.1%	12.6%
Jet Tagging	2582	34.9%	4.41%
Central Jet Veto	1998	77.4%	3.41%
b -jet Veto	1925	96.3%	3.29%
$P_T^{\ell\ell} > 30\text{ GeV}$	1570	81.6%	2.68%
$Z \rightarrow \tau\tau$ Rejection	1563	99.6%	2.67%
$m_{\ell\ell} < 50\text{ GeV}$	1004	64.2%	1.71%
Azimuthal Separation	869	86.6%	1.48%
Transverse Mass Cut	796	91.6%	1.36%

Table A.33: Cutflow table for the $e\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

A.8. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	8707	16.6%	14.9%
2 Good Non isolated leptons	8707	100%	14.9%
Exactly 2 opposite sign lep	8081	92.8%	13.8%
$m_{\ell\ell} > 15\text{ GeV}$	7328	90.7%	12.5%
p_T^{miss}	5324	72.7%	9.09%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	5269	99%	9%
Jet Tagging	1900	36.1%	3.24%
Central Jet Veto	1527	80.4%	2.61%
b -jet Veto	1454	95.2%	2.48%
$P_T^{\ell\ell} > 30\text{ GeV}$	1188	81.7%	2.03%
$Z \rightarrow \tau\tau$ Rejection	1183	99.6%	2.02%
$m_{\ell\ell} < 50\text{ GeV}$	817	69.1%	1.39%
Azimuthal Separation	733	89.7%	1.25%
Transverse Mass Cut	656	89.5%	1.12%

Table A.34: Cutflow table for the $\mu\mu$ channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

cut	MC events	Relative eff [%]	Total eff [%]
Total No events	64812		
Sum of Weights	58574		
L1 TRIGGER	55884	95.4%	95.4%
L2 TRIGGER	54205	97%	92.5%
EF TRIGGER	52355	96.6%	89.4%
Second lepton with $P_T > 10\text{GeV}$	9932	19%	17%
2 Good Non isolated leptons	4536	45.7%	7.74%
Exactly 2 opposite sign lep	3955	87.2%	6.75%
$m_{\ell\ell} > 15\text{ GeV}$	3615	91.5%	6.17%
p_T^{miss}	2451	67.8%	4.18%
$m_T^{\ell\ell\nu} > 30\text{ GeV}$	2422	98.8%	4.13%
Jet Tagging	877	36.2%	1.5%
Central Jet Veto	665	75.8%	1.14%
b -jet Veto	637	95.8%	1.09%
$P_T^{\ell\ell} > 30\text{ GeV}$	519	81.5%	0.886%
$Z \rightarrow \tau\tau$ Rejection	514	99%	0.878%
$m_{\ell\ell} < 50\text{ GeV}$	327	63.6%	0.558%
Azimuthal Separation	286	87.5%	0.488%
Transverse Mass Cut	271	94.8%	0.463%

Table A.35: Cutflow table for the ee channel, for a signal MC sample with $m_H=170\text{ GeV}$ in the conservative scenario

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$e\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	1.46	3.14	0.37	4.50	1.06	–
130	3.63	3.93	0.51	6.08	1.06	–
140	6.49	5.70	0.66	7.95	1.06	–
150	8.70	6.94	0.80	9.38	1.06	–
160	12.6	8.12	0.95	10.3	1.06	–
165	14.6	8.72	1.00	10.7	1.06	–
170	12.2	9.85	1.05	11.2	1.06	–
180	9.12	11.0	1.11	11.3	1.06	–
190	5.98	11.3	1.14	11.5	1.06	–
200	3.93	11.4	1.15	11.6	1.06	–

$\mu\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.77	2.13	0.22	3.16	–	–
130	2.10	2.60	0.33	4.70	–	–
140	4.05	3.60	0.44	5.85	–	–
150	4.41	4.85	0.58	6.66	–	–
160	11.0	6.17	0.68	7.48	–	–
165	9.61	6.71	0.72	8.00	–	–
170	9.37	6.91	0.75	8.29	–	–
180	6.47	7.31	0.81	8.58	–	–
190	3.89	7.65	0.84	8.77	–	–
200	2.68	7.65	0.85	8.91	–	–

ee Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.28	0.87	0.11	1.18	1.05	0
130	0.93	0.99	0.16	1.62	1.05	0
140	1.80	1.59	0.23	2.16	1.05	2.76
150	2.80	2.18	0.26	2.74	1.05	2.76
160	3.00	2.71	0.27	3.18	1.05	2.76
165	4.62	3.03	0.28	3.14	1.05	2.76
170	3.83	3.15	0.29	3.14	1.05	2.76
180	1.98	3.34	0.31	3.38	1.05	2.76
190	2.28	3.54	0.31	3.43	1.05	2.76
200	1.22	3.54	0.31	3.48	1.05	2.76

Table A.36: Cross-sections after cuts in the signal region, for various Higgs boson masses at a center-of-mass energy of 10 TeV, using the cuts defined for the aggressive scenario.

A.8. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

$e\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.46	2.77	0.15	2.44	–	–
130	1.29	3.91	0.22	3.30	–	–
140	2.68	6.25	0.33	4.21	–	–
150	4.72	8.45	0.43	5.17	–	–
160	6.64	9.90	0.56	5.79	–	–
165	8.88	10.3	0.60	6.12	–	–
170	7.51	11.5	0.64	6.65	–	–
180	6.09	12.4	0.70	6.75	–	–
190	4.03	13.2	0.71	6.94	–	–
200	2.73	13.3	0.73	7.08	–	–

$\mu\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.29	1.88	0.13	1.77	–	–
130	0.94	2.97	0.18	2.59	–	–
140	2.01	3.83	0.27	3.40	–	–
150	1.94	4.54	0.37	3.93	–	–
160	5.31	5.93	0.46	4.41	–	–
165	6.07	6.59	0.48	4.89	–	–
170	6.12	6.99	0.50	5.03	–	–
180	4.24	7.67	0.55	5.22	–	–
190	2.32	8.28	0.56	5.42	–	–
200	1.88	8.42	0.58	5.51	–	–

ee Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.14	1.63	0.06	0.24	–	–
130	0.43	1.89	0.09	0.67	–	–
140	0.91	3.12	0.14	0.96	–	–
150	1.77	3.78	0.16	1.39	–	–
160	2.15	4.17	0.16	1.63	–	–
165	2.91	4.63	0.18	1.58	–	–
170	2.58	4.82	0.18	1.58	–	–
180	1.94	4.80	0.20	1.73	–	–
190	1.73	5.00	0.20	1.73	–	–
200	0.82	5.00	0.21	1.78	–	–

Table A.37: Cross-sections after cuts, for various Higgs boson masses at a center-of-mass energy of 10 TeV, using the cuts defined for the conservative scenario.

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<i>eμ</i> Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W+jets	Z+jets
120	1.39	4.47	0.33	4.98	1.06	–
130	3.42	5.39	0.47	6.89	1.06	–
140	6.12	7.30	0.63	8.47	1.06	–
150	8.46	9.15	0.75	9.86	1.06	–
160	11.5	10.8	0.88	10.7	1.06	–
165	14.0	11.4	0.93	11.1	1.06	–
170	11.5	12.5	0.97	11.6	1.06	–
180	9.14	13.5	1.03	11.8	1.06	–
190	5.78	13.9	1.04	12.0	1.06	–
200	3.73	14.1	1.06	12.1	1.06	–

<i>μμ</i> Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W+jets	Z+jets
120	0.71	2.86	0.20	3.26	1.10	
130	1.89	3.33	0.30	4.79	1.10	
140	3.68	4.74	0.40	5.99	1.10	
150	4.64	6.33	0.52	6.95	1.10	
160	10.4	7.56	0.62	7.76	1.10	
165	8.59	8.38	0.64	8.24	1.10	
170	8.34	8.98	0.67	8.43	1.10	
180	6.43	9.58	0.73	8.72	1.10	
190	3.41	9.92	0.75	8.96	1.10	
200	2.49	9.92	0.76	9.10	1.10	

<i>ee</i> Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W+jets	Z+jets
120	0.29	0.92	0.12	1.25	1.05	0
130	0.94	1.60	0.17	1.78	1.05	0
140	1.76	2.34	0.24	2.50	1.05	2.76
150	2.90	3.06	0.28	3.07	1.05	2.76
160	2.90	3.79	0.29	3.55	1.05	2.76
165	4.49	4.25	0.30	3.55	1.05	2.76
170	3.94	4.38	0.31	3.55	1.05	2.76
180	2.48	4.50	0.32	3.74	1.05	2.76
190	2.30	4.70	0.33	3.84	1.05	2.76
200	1.18	4.70	0.33	3.89	1.05	2.76

Table A.38: Cross-sections after cuts, for various Higgs boson masses at a center-of-mass energy of 10 TeV, using the cuts defined for the acceptance challenge.

A.8. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

$e\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.77	1.04	0.18	3.06	0.74	–
130	1.88	1.51	0.25	4.10	0.74	–
140	3.32	2.31	0.32	5.33	0.74	–
150	4.32	2.83	0.38	6.26	0.74	–
160	6.40	3.38	0.46	6.87	0.74	–
165	7.17	3.58	0.48	7.17	0.74	–
170	5.93	3.92	0.51	7.47	0.74	–
180	4.44	4.50	0.54	7.57	0.74	–
190	2.93	4.66	0.55	7.66	0.74	–
200	1.87	4.68	0.55	7.73	0.74	–

$\mu\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.40	0.85	0.10	1.97	–	–
130	1.08	1.08	0.16	3.05	–	–
140	2.04	1.60	0.21	3.87	–	–
150	2.24	2.08	0.27	4.44	–	–
160	5.30	2.75	0.33	5.01	–	–
165	4.70	3.03	0.34	5.35	–	–
170	4.54	3.07	0.36	5.52	–	–
180	3.04	3.32	0.38	5.72	–	–
190	1.90	3.49	0.40	5.83	–	–
200	1.23	3.49	0.40	5.92	–	–

ee Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.15	0.40	0.05	0.92	0.54	–
130	0.49	0.40	0.07	1.27	0.54	–
140	0.92	0.66	0.11	1.64	0.54	1.47
150	1.43	0.93	0.12	1.96	0.54	1.47
160	1.53	1.13	0.13	2.22	0.54	1.47
165	2.32	1.26	0.13	2.19	0.54	1.47
170	1.90	1.30	0.14	2.19	0.54	1.47
180	0.95	1.38	0.15	2.34	0.54	1.47
190	1.09	1.45	0.15	2.37	0.54	1.47
200	0.58	1.45	0.15	2.40	0.54	1.47

Table A.39: Cross-sections after cuts in the signal region, for various Higgs boson masses at a center-of-mass energy of 7 TeV, using the cuts defined for the aggressive scenario.

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$e\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.24	1.21	0.07	1.51	–	–
130	0.66	1.86	0.10	2.12	–	–
140	1.36	2.90	0.15	2.72	–	–
150	2.41	3.74	0.21	3.27	–	–
160	3.35	4.35	0.27	3.67	–	–
165	4.33	4.45	0.29	3.90	–	–
170	3.68	4.82	0.31	4.24	–	–
180	2.95	5.24	0.33	4.30	–	–
190	1.99	5.57	0.34	4.42	–	–
200	1.29	5.64	0.35	4.52	–	–

$\mu\mu$ Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.15	0.77	0.06	1.01	–	–
130	0.47	1.20	0.09	1.55	–	–
140	0.99	1.69	0.13	2.15	–	–
150	0.99	1.92	0.18	2.53	–	–
160	2.46	2.60	0.22	2.85	–	–
165	2.98	2.97	0.23	3.17	–	–
170	2.97	3.13	0.24	3.25	–	–
180	2.05	3.44	0.26	3.38	–	–
190	1.17	3.73	0.27	3.48	–	–
200	0.86	3.78	0.27	3.53	–	–

ee Channel						
m_H [GeV]	Signal	$t\bar{t} + Wt$	$gg \rightarrow WW$	$qq \rightarrow WW$	W +jets	Z +jets
120	0.07	0.66	0.03	0.14	–	–
130	0.22	0.71	0.04	0.44	–	–
140	0.46	1.27	0.06	0.61	–	–
150	0.90	1.58	0.07	0.89	–	–
160	1.10	1.76	0.08	1.06	–	–
165	1.47	1.91	0.08	1.03	–	–
170	1.26	1.97	0.09	1.03	–	–
180	0.94	1.95	0.09	1.10	–	–
190	0.85	2.01	0.09	1.10	–	–
200	0.39	2.01	0.10	1.13	–	–

Table A.40: Cross-sections after cuts in the signal region, for various Higgs boson masses at a center-of-mass energy of 7 TeV, using the cuts defined for the conservative scenario.

A.8. $H \rightarrow WW \rightarrow \ell \nu \ell \nu + 1j$ additional information

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	b -tagged
Signal($m_H = 120$ GeV)	0.00	–	–	0.40	0.04
Signal($m_H = 130$ GeV)	0.04	–	0.00	0.87	0.10
Signal($m_H = 140$ GeV)	0.21	0.00	0.02	1.47	0.22
Signal($m_H = 150$ GeV)	0.55	–	0.10	2.04	0.34
Signal($m_H = 160$ GeV)	0.88	–	0.22	2.67	0.31
Signal($m_H = 165$ GeV)	0.64	0.00	0.06	2.73	0.44
Signal($m_H = 170$ GeV)	1.04	0.06	0.12	2.21	0.45
Signal($m_H = 180$ GeV)	2.16	0.10	0.39	1.58	0.33
Signal($m_H = 190$ GeV)	2.81	0.35	1.04	1.13	0.21
Signal($m_H = 200$ GeV)	3.75	0.38	0.93	0.74	0.10
$t\bar{t}$	59.2	14.8	28.2	3.23	50.76
$gg \rightarrow WW$	2.09	0.49	0.89	0.30	0.02
$qq \rightarrow WW$	41.8	7.82	17.3	3.87	0.53
W +jets	5.29	–	–	246.5	–
Z +jets	–	–	0.43	0.83	0.08

Table A.41: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the aggressive scenario.

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	b -tagged
Signal($m_H = 120$ GeV)	–	–	–	0.11	0.02
Signal($m_H = 130$ GeV)	0.01	–	0.00	0.32	0.06
Signal($m_H = 140$ GeV)	0.05	–	0.00	0.62	0.15
Signal($m_H = 150$ GeV)	0.32	–	–	0.68	0.33
Signal($m_H = 160$ GeV)	0.34	–	0.11	1.53	0.08
Signal($m_H = 165$ GeV)	0.20	0.00	0.01	1.81	0.34
Signal($m_H = 170$ GeV)	0.42	0.01	0.07	1.42	0.38
Signal($m_H = 180$ GeV)	1.01	0.10	0.23	0.87	0.32
Signal($m_H = 190$ GeV)	1.35	0.21	0.78	0.85	0.21
Signal($m_H = 200$ GeV)	2.16	0.27	0.63	0.45	0.07
$t\bar{t}$	61.8	18.3	31.7	2.75	45.82
$gg \rightarrow WW$	1.25	0.34	0.62	0.18	0.02
$qq \rightarrow WW$	21.4	5.04	11.0	1.82	0.43
W +jets	–	–	–	72.8	–
Z +jets	–	–	4.03	0.40	–

Table A.42: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the conservative scenario.

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Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	b -tagged
Signal($m_H = 120$ GeV)	0.00	–	–	0.38	0.04
Signal($m_H = 130$ GeV)	0.04	–	0.00	0.88	0.10
Signal($m_H = 140$ GeV)	0.21	0.01	0.02	1.45	0.19
Signal($m_H = 150$ GeV)	0.32	–	0.10	1.90	0.34
Signal($m_H = 160$ GeV)	0.91	–	0.22	2.80	0.22
Signal($m_H = 165$ GeV)	0.54	0.00	0.05	2.79	0.44
Signal($m_H = 170$ GeV)	0.92	0.06	0.10	2.30	0.44
Signal($m_H = 180$ GeV)	2.44	0.10	0.47	1.76	0.42
Signal($m_H = 190$ GeV)	2.72	0.30	1.07	1.26	0.14
Signal($m_H = 200$ GeV)	3.50	0.44	0.88	0.76	0.10
$t\bar{t}$	74.9	16.9	33.9	3.82	52.31
$gg \rightarrow WW$	2.09	0.51	0.87	0.27	0.03
$qq \rightarrow WW$	44.0	8.54	17.7	3.92	0.57
W +jets	4.23	–	–	246.5	–
Z +jets	–	–	0.43	0.83	–

Table A.43: Cross-sections after cuts in the various control regions for a center-of-mass energy of 10 TeV, using the cuts defined for the acceptance challenge.

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	b -tagged
Signal($m_H = 120$ GeV)	0.00	–	–	0.21	0.02
Signal($m_H = 130$ GeV)	0.02	–	0.00	0.45	0.05
Signal($m_H = 140$ GeV)	0.11	0.00	0.01	0.74	0.12
Signal($m_H = 150$ GeV)	0.31	–	0.05	1.01	0.15
Signal($m_H = 160$ GeV)	0.44	–	0.11	1.29	0.15
Signal($m_H = 165$ GeV)	0.32	0.00	0.03	1.34	0.21
Signal($m_H = 170$ GeV)	0.51	0.03	0.06	1.08	0.22
Signal($m_H = 180$ GeV)	1.06	0.05	0.20	0.74	0.16
Signal($m_H = 190$ GeV)	1.36	0.17	0.49	0.54	0.10
Signal($m_H = 200$ GeV)	1.78	0.18	0.44	0.35	0.04
$t\bar{t}$	23.5	6.23	10.8	1.15	21.61
$gg \rightarrow WW$	0.95	0.21	0.38	0.14	0.01
$qq \rightarrow WW$	26.2	4.92	10.9	2.69	0.35
W +jets	3.08	–	–	167	–
Z +jets	–	–	0.30	0.44	0.00

Table A.44: Cross-sections after cuts in the various control regions for a center-of-mass energy of 7 TeV, using the cuts defined for the aggressive scenario.

A.8. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 1j$ additional information

Process	$WW(e\mu)$	$WW(ee)$	$WW(\mu\mu)$	Reverse IsEM	b -tagged
Signal($m_H = 120$ GeV)	–	–	–	0.06	0.01
Signal($m_H = 130$ GeV)	0.00	–	0.00	0.16	0.03
Signal($m_H = 140$ GeV)	0.03	–	0.00	0.30	0.08
Signal($m_H = 150$ GeV)	0.18	–	–	0.34	0.15
Signal($m_H = 160$ GeV)	0.17	–	0.06	0.78	0.04
Signal($m_H = 165$ GeV)	0.10	0.00	0.01	0.89	0.16
Signal($m_H = 170$ GeV)	0.21	0.01	0.03	0.69	0.18
Signal($m_H = 180$ GeV)	0.53	0.05	0.12	0.42	0.15
Signal($m_H = 190$ GeV)	0.67	0.10	0.35	0.41	0.10
Signal($m_H = 200$ GeV)	1.02	0.13	0.30	0.21	0.03
$t\bar{t}$	24.2	7.32	11.7	1.03	19.1
$gg \rightarrow WW$	0.55	0.15	0.26	0.08	0.01
$qq \rightarrow WW$	12.5	3.08	6.60	1.26	0.29
W +jets	–	–	–	43.2	–
Z +jets	–	–	1.87	0.22	–

Table A.45: Cross-sections after cuts in the various control regions for a center-of-mass energy of 7 TeV, using the cuts defined for the conservative scenario.

A.9 $H \rightarrow WW \rightarrow \ell \nu \ell \nu + 2j$ additional information

A.9.1 Supporting material for the physics objects selection

Figure A.36 contains distributions of some of the kinematic variables of muons for signal and main backgrounds at 10 TeV.

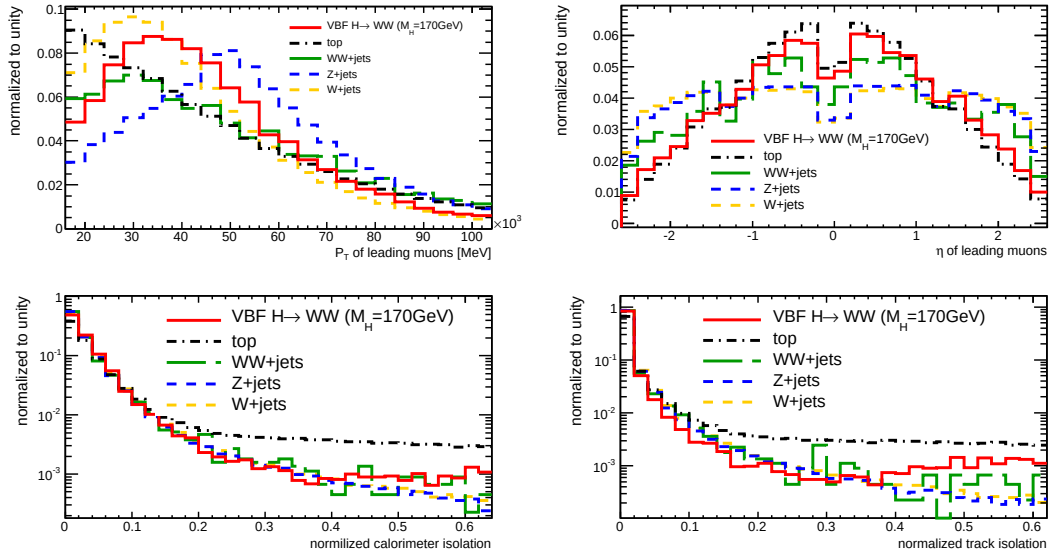


Figure A.36: Muon kinematics for signal and main backgrounds.

A.9.2 Cutflow for the Aggressive and Conservative scenarios

Cutflow tables in the Signal Region for the conservative scenario

Tables A.46, A.47, A.48, A.49 shows cutflows in the Signal Region for signal and main backgrounds at 10 TeV in case of the conservative scenario. The sum of the three flavor channels and a breakdown in the three are presented.

	signal (fb)	background (fb)					total
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	di-jets	
lepton acceptance	27.45	1220.79	8695.06	1504.30	880895.82	272.69	892588.66
3^{rd} lepton veto	27.43	1219.88	8644.76	1484.91	880599.62	272.69	892221.86
$p_T^{lead.lep.} > 40$ GeV	27.43	1219.88	8644.76	1484.91	880599.62	272.69	892221.86
m_{ll} cuts	25.78	1124.37	7946.90	806.20	121039.00	240.61	131157.08
$p_T^{mis} > 30/40$ GeV	21.88	703.29	6434.83	410.97	552.36	–	8101.44
$m_T^{ll\nu} > 30$ GeV	20.78	664.28	5658.47	399.42	224.23	–	6946.41
jet acceptance	15.11	148.05	5056.75	58.31	121.73	–	5384.85
jet-veto	12.94	103.06	2021.83	38.63	63.64	–	2227.15
b-veto (SV0)	12.02	94.55	466.29	35.99	52.05	–	648.88
$\eta_{j1} \cdot \eta_{j2} < 0$	10.64	39.10	197.83	14.15	21.18	–	272.28
$p_T^{lead.jet} > 40$ GeV	9.61	27.94	165.99	8.38	19.67	–	221.98
$\Delta\eta_{jj} > 3.8$	7.20	4.60	24.18	0.12	3.48	–	32.37
$m_{jj} > 500$ GeV	5.98	2.60	11.35	–	2.42	–	16.37
$p_T^{tot} < 30$ GeV	5.72	2.12	7.86	–	2.42	–	12.41
$Z \rightarrow \tau\tau$ rejection	5.59	1.87	7.04	–	1.18	–	10.08
$m_{ll} < 80$ GeV	5.44	0.62	1.34	–	1.18	–	3.14
$\Delta\phi_{ll} < 1.6$	4.53	0.38	0.80	–	1.18	–	2.36
$m_T < m_H$	4.23	0.26	0.52	–	–	–	0.78

Table A.46: Cutflow for signal Monte Carlo signal sample ($m_H = 170$ GeV) and all relevant backgrounds in the Signal region for the conservative scenario. Cross-sections are summed over ee , $e\mu$ and $\mu\mu$ channels. $W + jets$ column includes contributions from WZ and Wbb . $Z + jets$ column includes ZZ and Zbb contributions. The column $di-jets$ includes contributions from $b\bar{b}$ background. The last row represents Monte Carlo statistical uncertainty. Cross-sections are given in fb.

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	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	di-jets	total
lepton acceptance	13.43	595.09	4247.15	492.71	3568.47	128.33	9031.74
3^{rd} lepton veto	13.41	594.31	4222.99	488.02	3565.68	128.33	8999.33
m_{ll} cuts	13.01	589.71	4187.64	464.31	3549.82	128.33	8919.80
$p_T^{mis} > 30/40$ GeV	11.51	408.99	3565.73	299.24	288.30	–	4562.27
$m_T^{ll\nu} > 30$ GeV	10.88	386.20	3104.04	289.38	74.05	–	3853.67
jet acceptance	7.95	86.06	2764.37	39.53	23.49	–	2913.45
jet-veto	6.82	59.19	1113.14	27.65	13.79	–	1213.77
b-veto (SV0)	6.30	53.67	262.94	27.27	12.46	–	356.34
$\eta_{j1} \cdot \eta_{j2} < 0$	5.59	21.79	108.80	11.38	6.69	–	148.67
$p_T^{lead.jet} > 40$ GeV	5.07	15.56	91.96	5.99	6.07	–	119.58
$\Delta\eta_{jj} > 3.8$	3.78	2.61	13.12	–	1.38	–	17.11
$m_{jj} > 500$ GeV	3.13	1.61	6.07	–	0.81	–	8.49
$p_T^{tot} < 30$ GeV	2.98	1.25	4.78	–	0.81	–	6.84
$Z \rightarrow \tau\tau$ rejection	2.91	1.25	4.50	–	–	–	5.75
$m_{ll} < 80$ GeV	2.78	0.51	0.66	–	–	–	1.17
$\Delta\phi_{ll} < 1.6$	2.34	0.38	0.60	–	–	–	0.98
$m_T < m_H$	2.20	0.26	0.46	–	–	–	0.72

Table A.47: Cross-sections in the Signal Region for $e\mu$ channel conservative scenario.

	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	di-jets	total
lepton acceptance	4.95	216.98	1596.38	555.40	306586.94	44.11	308999.81
3^{rd} lepton veto	4.95	216.98	1585.43	547.00	306482.69	44.11	308876.22
m_{ll} cuts	4.49	185.83	1354.60	275.17	40076.41	36.09	41928.10
$p_T^{mis} > 30/40$ GeV	3.59	96.59	1026.76	95.59	78.81	–	1297.75
$m_T^{ll\nu} > 30$ GeV	3.42	90.18	909.17	94.94	38.51	–	1132.80
jet acceptance	2.49	19.28	811.05	13.72	26.89	–	870.94
jet-veto	2.15	13.15	330.13	8.60	16.37	–	368.24
b-veto (SV0)	1.99	12.39	75.09	7.49	13.61	–	108.58
$\eta_{j1} \cdot \eta_{j2} < 0$	1.78	5.83	35.29	2.19	3.04	–	46.34
$p_T^{lead.jet} > 40$ GeV	1.62	3.69	30.07	2.04	3.00	–	38.80
$\Delta\eta_{jj} > 3.8$	1.21	0.87	3.90	–	0.41	–	5.18
$m_{jj} > 500$ GeV	1.00	0.38	2.00	–	–	–	2.38
$p_T^{tot} < 30$ GeV	0.96	0.38	1.44	–	–	–	1.83
$Z \rightarrow \tau\tau$ rejection	0.93	0.13	1.31	–	–	–	1.43
$m_{ll} < 80$ GeV	0.92	–	0.61	–	–	–	0.61
$\Delta\phi_{ll} < 1.6$	0.76	–	0.20	–	–	–	0.20
$m_T < m_H$	0.73	–	0.06	–	–	–	0.06

Table A.48: Cross-sections in the Signal Region for ee channel conservative scenario.

A.9. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 2j$ additional information

	signal (fb)	background (fb)					
	<i>VBF</i>	<i>WW</i>	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	<i>di-jets</i>	<i>total</i>
lepton acceptance	9.08	408.72	2851.54	456.19	570740.41	100.25	574557.11
3^{rd} lepton veto	9.07	408.59	2836.33	449.88	570551.24	100.25	574346.30
m_{ll} cuts	8.28	348.83	2404.67	66.71	77412.77	76.19	80309.18
$p_T^{mis} > 30/40$ GeV	6.78	197.70	1842.34	16.13	185.25	–	2241.42
$m_T^{ll\nu} > 30$ GeV	6.48	187.90	1645.27	15.10	111.67	–	1959.93
jet acceptance	4.67	42.71	1481.33	5.07	71.35	–	1600.46
jet-veto	3.97	30.72	578.56	2.38	33.48	–	645.14
b-veto (SV0)	3.72	28.49	128.27	1.23	25.99	–	183.97
$\eta_{j1} \cdot \eta_{j2} < 0$	3.27	11.49	53.75	0.58	11.46	–	77.27
$p_T^{lead,jet} > 40$ GeV	2.91	8.69	43.96	0.35	10.60	–	63.60
$\Delta\eta_{jj} > 3.8$	2.21	1.12	7.16	0.12	1.69	–	10.09
$m_{jj} > 500$ GeV	1.85	0.61	3.29	–	1.61	–	5.51
$p_T^{tot} < 30$ GeV	1.78	0.49	1.64	–	1.61	–	3.74
$Z \rightarrow \tau\tau$ rejection	1.76	0.49	1.23	–	1.18	–	2.90
$m_{ll} < 80$ GeV	1.75	0.11	0.06	–	1.18	–	1.35
$\Delta\phi_{ll} < 1.6$	1.42	–	–	–	1.18	–	1.18
$m_T < m_H$	1.30	–	–	–	–	–	–

Table A.49: Cross-sections in the Signal Region for $\mu\mu$ channel conservative scenario.

Appendix A. Appendix

Cutflow tables in Control Regions for the conservative scenario

Effective cross-sections after successive cuts in Control Regions at 10 TeV for the conservative scenario can be found in Tables A.50, A.51, A.52.

flavor channel	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	$di\text{-}jets$	$total$
Signal Control Region							
$e\mu$	2.20±0.06	0.26±0.18	0.46±0.22	–	–	–	0.72±0.29
ee	0.73±0.04	–	0.06±0.06	–	–	–	0.06±0.06
$\mu\mu$	1.30±0.05	–	–	–	–	–	–
total	4.23±0.09	0.26±0.18	0.52±0.23	–	–	–	0.78±0.29
top Control Region							
$e\mu$	–	1.11±0.37	105.64±3.76	0.12±0.12	0.05±0.05	–	106.91±3.78
ee	–	–	28.82±1.96	–	–	–	28.82±1.96
$\mu\mu$	–	0.13±0.13	46.61±2.50	–	0.04±0.04	–	46.77±2.50
total	0.01±0.004	1.24±0.39	181.07±4.93	0.12±0.12	0.09±0.06	–	182.51±4.94
WW Control Region							
$e\mu$	0.04±0.01	2.75±0.59	26.27±1.85	0.12±0.12	0.41±0.41	–	29.54±1.98
ee	–	0.51±0.26	8.49±1.06	–	–	–	9.00±1.09
$\mu\mu$	–	2.50±0.56	11.19±1.20	–	0.49±0.43	–	14.17±1.40
total	0.04±0.01	5.76±0.85	45.95±2.45	0.12±0.12	0.89±0.59	–	52.72±2.66

Table A.50: Effective cross-sections (in fb) in the Signal and Control Regions and corresponding Monte Carlo uncertainties. conservative scenario.

	signal (fb)	background (fb)					total
	<i>VBF</i>	<i>WW</i>	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	<i>di-jets</i>	
jet acceptance	15.11	148.05	5056.75	58.31	121.73	–	5384.85
jet-veto	12.94	103.06	2021.83	38.63	63.64	–	2227.15
b-jet tagging	0.92	8.51	1555.54	2.64	11.58	–	1578.27
$\eta_{j1} \cdot \eta_{j2} < 0$	0.79	4.05	679.70	2.37	2.45	–	688.57
$p_T^{lead.jet} > 40$ GeV	0.77	3.80	634.44	2.37	2.30	–	642.90
$\Delta\eta_{jj} < 3.8$	0.30	3.44	601.85	1.22	2.11	–	608.62
$m_{jj} < 500$ GeV	0.22	2.70	586.31	1.22	1.96	–	592.18
$p_T^{tot} < 30$ GeV	0.20	2.59	456.78	1.22	1.87	–	462.46
$Z \rightarrow \tau\tau$ rejection	0.20	2.59	430.93	1.22	1.64	–	436.37
$m_{ll} > 80$ GeV	0.01	1.71	227.33	0.12	0.13	–	229.29
$\Delta\phi_{ll} > 1.6$	0.01	1.24	181.07	0.12	0.09	–	182.51

Table A.51: Cutflow for the top control region. Cross-sections (in fb) are summed over ee , $e\mu$ and $\mu\mu$ channels. conservative scenario.

A.9. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 2j$ additional information

	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	$di\text{-}jets$	total
jet acceptance	15.11	148.05	5056.75	58.31	121.73	–	5384.85
jet-veto	12.94	103.06	2021.83	38.63	63.64	–	2227.15
b-veto (SV0)	12.02	94.55	466.29	35.99	52.05	–	648.88
$\eta_{j1} \cdot \eta_{j2} < 0$	10.64	39.10	197.83	14.15	21.18	–	272.28
$p_T^{lead.j\bar{e}t} > 40 \text{ GeV}$	9.61	27.94	165.99	8.38	19.67	–	221.98
$\Delta\eta_{jj} < 3.8$	2.41	23.35	141.80	8.27	16.19	–	189.61
$m_{jj} < 500 \text{ GeV}$	1.98	21.58	136.37	8.03	12.55	–	178.53
$p_T^{tot} < 30 \text{ GeV}$	1.84	18.58	104.91	7.49	9.95	–	140.94
$Z \rightarrow \tau\tau$ rejection	1.82	17.74	97.88	7.49	4.05	–	127.17
$m_{ll} > 80 \text{ GeV}$	0.06	8.37	56.50	0.26	1.44	–	66.57
$\Delta\phi_{ll} > 1.6$	0.04	5.76	45.95	0.12	0.89	–	52.72

Table A.52: Cutflow for the WW control region. Cross-sections (in fb) are summed over ee , $e\mu$ and $\mu\mu$ channels. conservative scenario.

Systematics.

Systematics uncertainties on extrapolation ratios for the conservative scenario at 10 TeV are shown in Table A.54. Table A.53 shows comparison of the ratios of cross-section between fast and full simulation and their statistical uncertainties.

	$\alpha_{top} \pm \Delta\alpha_{top}^{stat}$	$\beta_{top} \pm \Delta\beta_{top}^{stat}$	$\alpha_{WW} \pm \Delta\alpha_{WW}^{stat}$
Full Simulation	0.0016 ± 0.0011	0.24 ± 0.02	0.04 ± 0.03
Fast Simulation	0.0088 ± 0.0009	0.222 ± 0.005	0.101 ± 0.007

Table A.53: Comparison between full and fast simulation of extrapolation ratios and their Monte Carlo errors. conservative scenario.

uncertainty	$\Delta\alpha_{top}^{syst}$	$\Delta\beta_{top}^{syst}$	$\Delta\alpha_{WW}^{syst}$
Q^2 scale	38%	8%	45%
jet energy scale (up)	8.07%	0.24%	14.95%
jet energy scale (down)	0.88%	0.19%	14.75%
jet energy resolution	0.81%	2.51%	0.40%
b-tagging efficiency	23.63%	35.70%	1.01%
light jet rejection	0.74%	0.20%	0.02%

Table A.54: Systematic uncertainties on extrapolation ratios based on fast simulation. conservative scenario.

A.9. $H \rightarrow WW \rightarrow \ell\nu\ell\nu + 2j$ additional information

Cutflow tables in the Signal Region for the aggressive scenario

A breakdown of the cutflow which were presented in Table 6.17 is given in Table A.55, A.56, A.57.

	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	di-jets	total
lepton acceptance	13.43	595.09	4251.41	492.71	3568.47	121.82	9029.50
3^{rd} lepton veto	13.41	594.31	4227.14	488.02	3565.68	121.82	8996.98
m_{ll} cuts	13.01	589.71	4191.62	464.31	3549.82	121.82	8917.28
$p_T^{mis} > 30/40$ GeV	11.51	408.99	3569.79	299.24	288.30	–	4566.33
$m_T^{ll\nu} > 30$ GeV	10.88	386.20	3107.30	289.38	74.05	–	3856.93
jet acceptance	7.95	86.06	2767.66	39.53	23.49	–	2916.75
jet-veto	6.82	59.19	1113.58	27.65	13.79	–	1214.21
b-veto (SV0)	6.30	53.67	263.27	27.27	12.46	–	356.68
$\eta_{j1} \cdot \eta_{j2} < 0$	5.59	21.79	109.01	11.38	6.69	–	148.88
$p_T^{lead,jet} > 40$ GeV	5.07	15.56	92.10	5.99	6.07	–	119.72
$\Delta\eta_{jj} > 3.8$	3.78	2.61	13.18	–	1.38	–	17.16
$p_T^{tot} < 30$ GeV	3.62	2.03	8.77	–	1.38	–	12.18
$Z \rightarrow \tau\tau$ rejection	3.53	1.92	8.21	–	0.12	–	10.25
$m_{ll} < 80$ GeV	3.38	1.06	1.96	–	0.12	–	3.14
$m_T < m_H$	3.21	0.93	1.56	–	0.12	–	2.61

Table A.55: Cross-sections in the Signal Region for $e\mu$ channel aggressive scenario.

	signal (fb)	background (fb)					
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	di-jets	total
lepton acceptance	4.95	216.98	1594.74	555.40	306586.94	46.21	309000.26
3^{rd} lepton veto	4.95	216.98	1583.74	547.00	306482.69	46.21	308876.62
m_{ll} cuts	4.49	185.83	1352.81	275.17	40076.41	37.81	41928.03
$p_T^{mis} > 30/40$ GeV	3.59	96.59	1025.29	95.59	78.81	–	1296.28
$m_T^{ll\nu} > 30$ GeV	3.42	90.18	907.68	94.94	38.51	–	1131.32
jet acceptance	2.49	19.28	809.62	13.72	26.89	–	869.51
jet-veto	2.15	13.15	329.56	8.60	16.37	–	367.68
b-veto (SV0)	1.99	12.39	75.01	7.49	13.61	–	108.49
$\eta_{j1} \cdot \eta_{j2} < 0$	1.78	5.83	35.17	2.19	3.04	–	46.22
$p_T^{lead,jet} > 40$ GeV	1.62	3.69	29.93	2.04	3.00	–	38.66
$\Delta\eta_{jj} > 3.8$	1.21	0.87	3.78	–	0.41	–	5.05
$p_T^{tot} < 30$ GeV	1.17	0.87	2.68	–	0.41	–	3.96
$Z \rightarrow \tau\tau$ rejection	1.13	0.61	2.48	–	–	–	3.10
$m_{ll} < 80$ GeV	1.12	0.24	0.62	–	–	–	0.85
$m_T < m_H$	1.08	0.11	0.34	–	–	–	0.45

Table A.56: Cross-sections in the Signal Region for ee channel aggressive scenario.

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	signal (fb)	background (fb)					
	<i>VBF</i>	<i>WW</i>	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	<i>di-jets</i>	<i>total</i>
lepton acceptance	9.08	408.72	2850.92	456.19	570740.41	105.02	574561.26
3^{rd} lepton veto	9.07	408.59	2835.65	449.88	570551.24	105.02	574350.38
m_{ll} cuts	8.28	348.83	2403.64	66.71	77412.77	79.81	80311.77
$p_T^{mis} > 30/40$ GeV	6.78	197.70	1841.36	16.13	185.25	–	2240.44
$m_T^{ll\nu} > 30$ GeV	6.48	187.90	1644.04	15.10	111.67	–	1958.70
jet acceptance	4.67	42.71	1479.80	5.07	71.35	–	1598.93
jet-veto	3.97	30.72	578.48	2.38	33.48	–	645.05
b-veto (SV0)	3.72	28.49	128.28	1.23	25.99	–	183.98
$\eta_{j1} \cdot \eta_{j2} < 0$	3.27	11.49	53.71	0.58	11.46	–	77.23
$p_T^{lead,jet} > 40$ GeV	2.91	8.69	43.88	0.35	10.60	–	63.52
$\Delta\eta_{jj} > 3.8$	2.21	1.12	7.19	0.12	1.69	–	10.12
$p_T^{tot} < 30$ GeV	2.13	1.00	4.29	0.12	1.65	–	7.06
$Z \rightarrow \tau\tau$ rejection	2.10	1.00	3.88	0.12	1.22	–	6.21
$m_{ll} < 80$ GeV	2.09	0.11	1.30	–	1.18	–	2.58
$m_T < m_H$	1.94	0.11	1.51	–	–	–	1.62

Table A.57: Cross-sections in the Signal Region for $\mu\mu$ channel aggressive scenario.

A.9.3 “Conservative” scenario for early data

It may be the case that the detector performance is not completely optimal in the very first data. Therefore an additional “conservative” scenario has been considered. Since the p_T threshold for jet selection might be sensitive to detector performance, it was changed from 20 GeV to 30 GeV for jets in the barrel and 40 GeV in the forward region ($3.2 < |\eta_j| < 4.8$). Missing energy can also be degraded and therefore a tighter cut on missing transverse momentum has been imposed: $p_T^{\text{miss}} > 50$ GeV (for all flavor channels). The impact parameter significance cuts for leptons are set to 6 and 9 for muons and electrons, respectively.

Effective cross-sections in the Signal Region and Control Regions for the “conservative” scenario are shown in Table A.58. Exclusion limits for 200, 500 and 1000 pb^{-1} of integrated luminosity at 10 TeV have been estimated for this scenario. Figures A.37, A.38, A.39 show corresponding curves.

	signal (fb) <i>VBF</i>	<i>WW</i>	<i>t</i> $\bar{t}$ + <i>Wt</i>	background (fb) <i>W</i> + <i>jets</i> <i>Z</i> + <i>jets</i> <i>total</i>		
Signal Region						
<i>eμ</i>	1.99±0.06	0.13±0.13	1.84±0.48	–	–	1.96±0.50
<i>ee</i>	0.83±0.04	–	0.89±0.35	–	–	0.89±0.35
<i>μμ</i>	1.29±0.05	0.11±0.11	1.17±0.40	–	–	1.28±0.41
total	4.11±0.08	0.24±0.17	3.90±0.71	–	–	4.14±0.73
Top Control Region						
<i>eμ</i>	0.01±0.00	1.07±0.36	130.63±4.21	1.15±1.15	–	132.85±4.38
<i>ee</i>	–	0.49±0.25	33.88±2.15	–	0.04±0.04	34.41±2.16
<i>μμ</i>	–	0.60±0.27	63.35±2.93	–	0.05±0.05	64.00±2.94
total	0.01±0.00	2.17±0.51	227.85±5.56	1.15±1.15	0.09±0.06	231.26±5.70
WW Control Region						
<i>eμ</i>	0.03±0.01	3.90±0.69	26.43±1.88	0.26±0.19	0.41±0.41	31.00±2.05
<i>ee</i>	–	0.96±0.34	9.78±1.14	0.12±0.12	0.41±0.41	11.27±1.27
<i>μμ</i>	–	2.82±0.59	12.54±1.30	0.12±0.12	0.12±0.08	15.60±1.43
total	0.04±0.01	7.68±0.97	48.76±2.55	0.50±0.25	0.93±0.58	57.87±2.80
Z Control Region						
<i>eμ</i>	0.05±0.01	1.99±0.50	8.18±1.04	1.42±1.17	0.41±0.41	11.99±1.69
<i>ee</i>	0.03±0.01	0.51±0.26	3.23±0.65	2.20±0.54	390.38±15.35	396.31±15.37
<i>μμ</i>	0.04±0.01	0.49±0.25	5.63±0.86	4.57±0.79	844.72±20.50	855.41±20.53
total	0.11±0.01	2.99±0.61	17.04±1.50	8.19±1.51	1235.50±25.61	1263.72±25.71

Table A.58: Effective cross-sections after cuts in the Signal Region and corresponding Control Regions for the “conservative” scenario at 10 TeV.

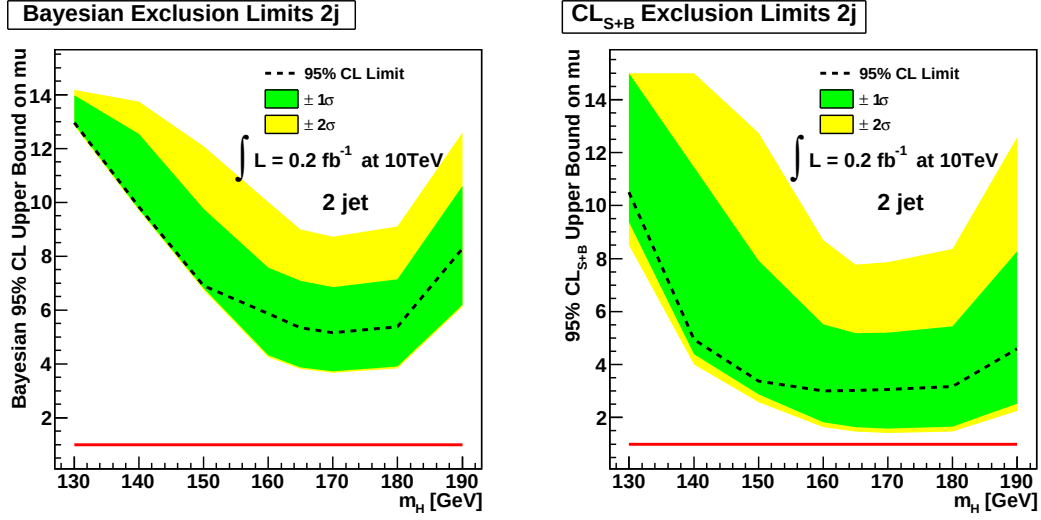


Figure A.37: Upper bound on the Standard Model Higgs boson cross-section with 200 pb^{-1} at 10 TeV. Bayesian and frequentist approaches. Conservative scenario.

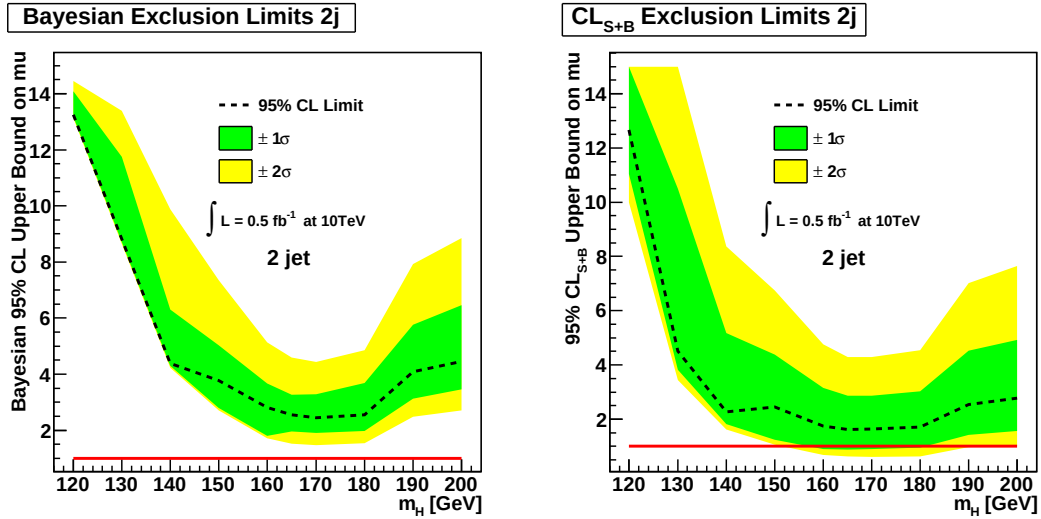


Figure A.38: Upper bound on the Standard Model Higgs boson cross-section with 500 pb^{-1} at 10 TeV. Bayesian and frequentist approaches. Conservative scenario.

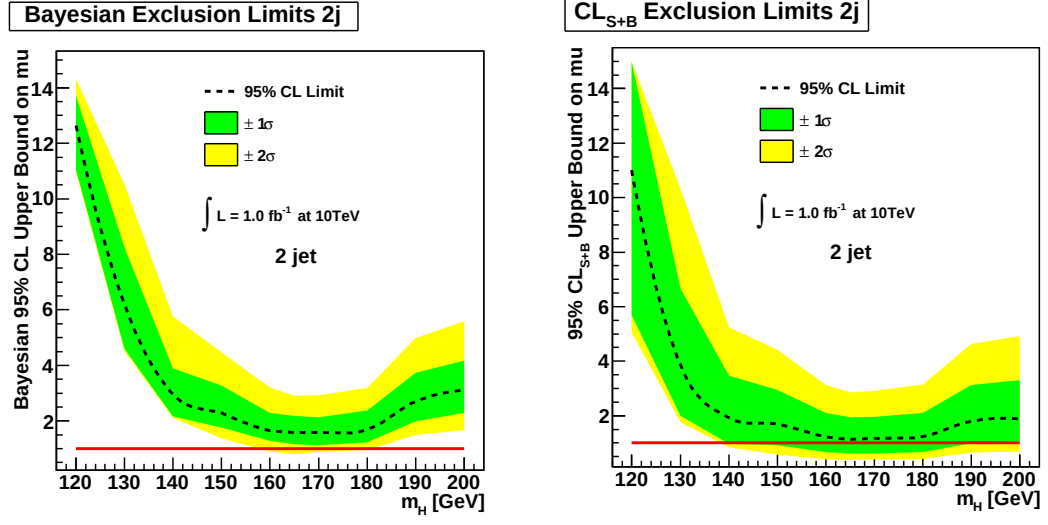


Figure A.39: Upper bound on the Standard Model Higgs boson cross-section with 1 fb^{-1} at 10 TeV. Bayesian and frequentist approaches. Conservative scenario.

A.9.4 Results at 7 TeV using PDF re-weighting tool for the “conservative” scenario

Table A.59 contains final effective cross-sections at 7 TeV for the aggressive scenario which are derived using the re-weighting tool.

Table A.59: Effective cross-sections after cuts in the Signal Region and corresponding Control Regions for the aggressive scenario at 7 TeV.

	signal (fb) <i>VBF</i>	background (fb)				
		<i>WW</i>	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	<i>total</i>
Signal Region						
$e\mu$	1.45±0.05	0.44±0.25	0.61±0.28	–	0.06±0.08	1.12±0.38
ee	0.47±0.03	0.06±0.08	0.06±0.08	–	–	0.12±0.11
$\mu\mu$	0.86±0.04	0.03±0.06	0.64±0.29	–	–	0.68±0.30
total	2.77±0.07	0.53±0.27	1.32±0.41	–	0.06±0.08	1.91±0.50
Top Control Region						
$e\mu$	0.01±0.00	0.72±0.30	54.86±2.74	0.06±0.08	0.02±0.03	55.66±2.76
ee	–	0.12±0.12	14.02±1.38	–	0.01±0.02	14.15±1.39
$\mu\mu$	–	0.26±0.18	24.16±1.82	–	0.03±0.03	24.45±1.83
total	0.01±0.00	1.11±0.37	93.05±3.57	0.06±0.08	0.06±0.05	94.27±3.59
WW Control Region						
$e\mu$	0.03±0.01	2.65±0.58	13.32±1.33	0.14±0.13	0.22±0.30	16.33±1.49
ee	–	0.42±0.23	4.01±0.74	0.05±0.08	0.22±0.30	4.69±0.83
$\mu\mu$	–	1.68±0.46	5.47±0.85	–	0.34±0.33	7.50±1.02
total	0.04±0.01	4.75±0.77	22.79±1.74	0.19±0.15	0.79±0.54	28.52±1.99
Z Control Region						
$e\mu$	0.03±0.01	1.03±0.36	3.64±0.70	0.14±0.13	0.22±0.30	5.03±0.85
ee	0.02±0.01	0.41±0.23	1.25±0.41	1.84±0.51	244.27±12.40	247.77±12.41
$\mu\mu$	0.02±0.01	0.49±0.25	1.98±0.51	2.54±0.60	612.50±22.28	617.51±22.29
total	0.07±0.01	1.93±0.49	6.86±0.95	4.52±0.80	857.00±25.50	870.31±25.53

For completeness results at 7 TeV for the “conservative” scenario are presented. Table A.60 contains effective cross-sections for the “conservative” scenario at 7 TeV. And Figures A.41, A.42 show the expected exclusion limit with 500 and 1000 pb^{−1} of data at 7 TeV for the “conservative” scenario. The case with 200 pb^{−1} is omitted because of the very poor sensitivity.

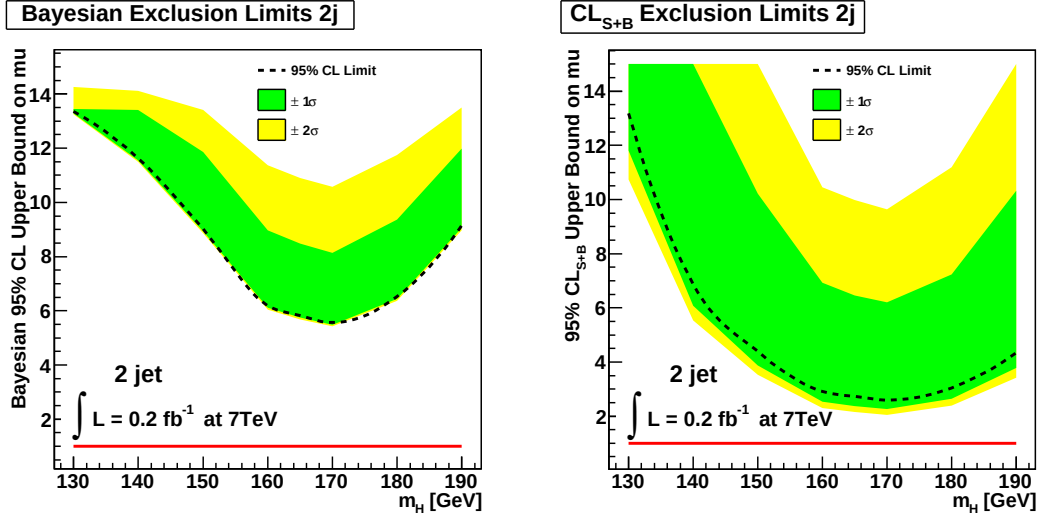


Figure A.40: Upper bound on the Standard Model Higgs boson cross-section with 200 pb^{-1} at 7 TeV. Bayesian and frequentist approaches. For the aggressive scenario.

	signal (fb)	background (fb)				
	VBF	WW	$t\bar{t} + Wt$	$W + jets$	$Z + jets$	total
Signal Region						
$e\mu$	0.87 ± 0.04	0.02 ± 0.05	0.58 ± 0.27	–	–	0.61 ± 0.27
ee	0.35 ± 0.02	–	0.26 ± 0.19	–	–	0.26 ± 0.19
$\mu\mu$	0.55 ± 0.03	0.03 ± 0.06	0.51 ± 0.26	–	–	0.54 ± 0.27
total	1.76 ± 0.05	0.05 ± 0.08	1.36 ± 0.42	–	–	1.41 ± 0.43
Top Control Region						
$e\mu$	–	0.49 ± 0.24	51.15 ± 2.64	1.02 ± 1.08	–	52.67 ± 2.86
ee	–	0.20 ± 0.16	13.15 ± 1.34	–	0.01 ± 0.02	13.36 ± 1.35
$\mu\mu$	–	0.26 ± 0.18	23.95 ± 1.80	–	0.01 ± 0.02	24.23 ± 1.81
total	–	0.96 ± 0.34	88.25 ± 3.46	1.02 ± 1.08	0.02 ± 0.03	90.25 ± 3.64
WW Control Region						
$e\mu$	0.02 ± 0.01	1.87 ± 0.48	10.33 ± 1.18	0.14 ± 0.13	0.22 ± 0.30	12.56 ± 1.31
ee	–	0.51 ± 0.25	3.68 ± 0.70	0.05 ± 0.08	0.22 ± 0.30	4.46 ± 0.81
$\mu\mu$	–	1.45 ± 0.42	4.71 ± 0.80	0.02 ± 0.04	0.04 ± 0.05	6.21 ± 0.90
total	0.02 ± 0.01	3.83 ± 0.69	18.71 ± 1.58	0.20 ± 0.16	0.48 ± 0.43	23.23 ± 1.79
Z Control Region						
$e\mu$	0.03 ± 0.01	1.09 ± 0.37	3.61 ± 0.69	0.85 ± 0.92	0.22 ± 0.30	5.77 ± 1.25
ee	0.02 ± 0.01	0.26 ± 0.18	1.47 ± 0.44	1.24 ± 0.41	221.39 ± 11.72	224.36 ± 11.74
$\mu\mu$	0.02 ± 0.01	0.23 ± 0.17	2.15 ± 0.53	2.57 ± 0.59	482.82 ± 16.41	487.77 ± 16.43
total	0.06 ± 0.01	1.57 ± 0.44	7.23 ± 0.98	4.67 ± 1.17	704.42 ± 20.16	717.90 ± 20.23

Table A.60: Effective cross-sections after cuts in the Signal Region and corresponding Control Regions for the “conservative” scenario at 7 TeV.

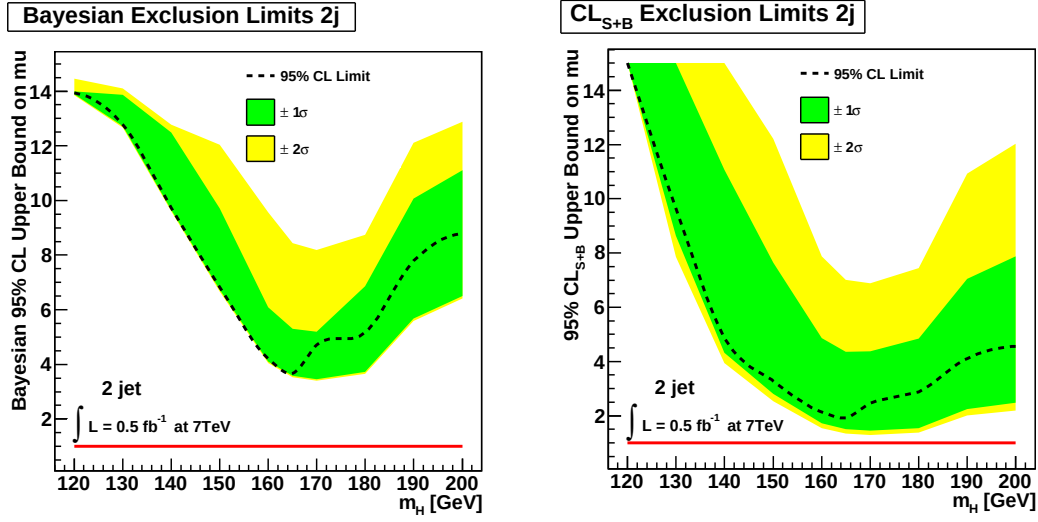


Figure A.41: Upper bound on the Standard Model Higgs boson cross-section with 500 pb^{-1} at 7 TeV. Bayesian and frequentist approaches. Conservative scenario.

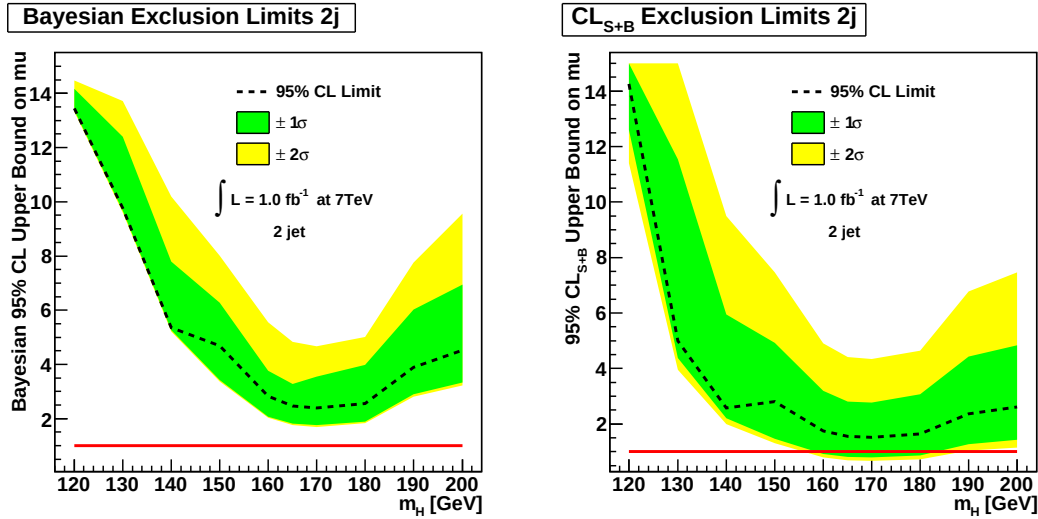


Figure A.42: Upper bound on the Standard Model Higgs boson cross-section with 1 pb^{-1} at 7 TeV. Bayesian and frequentist approaches. Conservative scenario.

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CERN-LHC, PhD in High Energy Physics, EPFL & University of Wisconsin
 — C++ programming expertise, BASH scripting and vectorial data handling —

CAREER

ASPIRATIONS

- **Particle Physics, Electroweak symmetry breaking. Higgs boson production processes and its search in leptonic signatures,**
- **Machine Learning. Statistical methods**
- **Parton distribution functions in particular EW and QCD constraints. Non perturbative regime.**
- **Data adquisition and Trigger infrastructure. Parallel computing, multicore processing and GPUs.**

EDUCATION AND RESEARCH

- † **Ph.D in Physics** (High Energy and Particle Physics) Jun. 2008 - Jun 2012.
 - At the **European Organization for Nuclear Research (CERN)**, under the Large Hadron Collider experiment, member of the **ATLAS** Collaboration in the search of the Higgs boson.
 - Hosted by the **Ecole Polytechnique Fédérale de Lausanne**, and funded by the **University of Wisconsin Madison** ATLAS research group
 - Thesis Title: *Standard Model Higgs searches in the weak boson decay channels with the ATLAS detector at the LHC*. With Prof. A. Bay and Prof. S. L. Wu.
- † Institute of Physics of Complex Matter (at the EPFL) Dec. 2007 - Jun. 2008. Characterization of ultra hard oxynitride nanocomposites, with a variety of techniques including x-ray, nanoindentation, TEM.
- † Diploma, or five (5) years equivalent, **Physics**. Jan. 2001 - Dec. 2006.
 - *Nuclear Physics, MC simulation of an instrument to find hidden objects using backscattering gamma radiation with GEANT4*. With Prof. F. Cristancho
- Universidad Nacional de Colombia Jan. 2005 - Dec. 2005. Hardware and Software for an holographic array of mico-lenses to sense wavefronts based on the Shack-Hartmann principle.
- Combustion Ingenieros Jan. 2002 - Jun. 2003. Design and development of automate systems for industrial hardware.

Graduate courses in quantum field theory, statistical mechanics, simulation methods, nuclear structure, particle physics, and some others.

TECHNICAL SKILLS

Expertise on massive parallel data analysis and simulation. Vast experience modeling complex systems, using Molecular Dynamics, Cellular Automata, Lattice-Boltzmann and specially **Monte-Carlo** methods. Particular interest in multivariate methods in **machine learning** algorithms. Background developing software for **real-time** hardware automation.

Wide-ranging programming and scripting experience with different languages: **C++/C**, **BASH**, **PYTHON**, and packages like **kdb+**, **MATLAB**, **MATHEMATICA**, **ROOT** or **TMVA** (for Machine Learning).

Usage of interfaces like **CONDOR**, **PROOF**, **BATCH** or **CUDA/GPUs** for **parallel/multi-core** analyses in local farms, or remote **GRID** clouds, primarily under **Linux** or Unix-like platforms.

Age:28, Colombian

LANGUAGE SKILLS

Fluent English, written and spoken. Native Spanish speaker, conversational French and basic notions of Italian.

WORK/TEACHING
EXPERIENCE

- Supervisor of PhDs and summer students: May. 2010 - present.
CERN/UW program, $Z \rightarrow ee$ observation and $H \rightarrow ZZ$ searches in ATLAS.
- Assistant, Thermodynamics Laboratory: Feb. 2008 - Jul. 2008.
Ecole Polytechnique Fédérale de Lausanne, for Life Science students.
- Titular Teacher: Jul. 2006 - Jul. 2007.
Conceptual Physics, Astronomy and Modern Physics Seminar, Colegio Calasanz.
- † Co-founder and Commercial manager: Nov. 2004 - Dec. 2006.
Colombiana de Confecciones Cerchar-Carrillo Ltda.
Bags & Accessories confection under the *2.22 brand* $\rightarrow$ fair-trade emphasis.

MISCELLANEOUS

- Conferences
 - DIVISION OF PARTICLES&FIELDS/**American Physical Society** 2011 and 2009.
Providence RI('11), Detroit MI('09), Speaker (*Higgs in the ATLAS Detector*).
 - LHC CROSS SECTIONS WORKSHOPS 2011 and 2010.
Brookhaven National Lab NY('11), U. Freiburg('10). (*PDFs - gluon-gluon-F.*).
 - ATLAS WORKSHOPS. (*Higgs searches*). 2011 and 2010.
Berkeley National Lab CA('11), U. Boston MA('11), U. Arlington TX US('10).
 - 6TH CONF. ON PHYSICS & ASTROPHYSICS OF QUARK GLUON PLASMA 2010.
Goa India, Invited for Plenary Talk (*First Results from ATLAS at the LHC*).
 - 5TH CERN LATINAMERICAN SCHOOL OF HEP 2009.
Antioquia Colombia, Assistant/presenter.
 - CONGRESO NACIONAL DE FISICA (COLOMBIA): 2001,2003,2005 and 2007.
XIX('01), XX('03), XXI('05), XXII('07) Assistant/presenter.
- 118 journal publications with the ATLAS Collaboration. Selected list (As editor):
 - *Combined search for a Standard Model Higgs Boson using up to 4.9^{-1} fb of pp at $\sqrt{s}=7$ TeV with ATLAS* **Phys. Lett. B to be published (2012)**.
 - *Search for a Standard Model Higgs Boson in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ decay channel* **Phys. Rev. Lett. 107, 221802 (2011)**.
 - *Limits on the production of the Standard Model Higgs Boson in p-p collisions at $\sqrt{s}=7$ TeV with the ATLAS detector* **arXiv:1106.2748v2[hep-ex] (2011)**.
 - *Search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^* \rightarrow 4\ell$ with the ATLAS detector* **Phys. Lett. B 705 (2011)**.
 - *ATLAS Sensitivity Prospects for Higgs Boson Production at the LHC Running at 7, 8 or 9 TeV*. **ATL-PHYS-PUB-2010-015 (2010)**.
 - *Prospects for Higgs Boson Searches using the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ Decay Mode with the ATLAS Detector for 10 TeV*. **ATL-PHYS-PUB-2010-005 (2010)**.

REFERENCES

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