



UNIVERSITY OF ROME TOR VERGATA

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**Study of the Higgs boson properties in
 $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with the
ATLAS detector at LHC using data
recorded at $\sqrt{s} = 8 - 13$ TeV**

Student:
Giada Mancini
mat: 0207607

Supervisor:
Prof.ssa Anna Di Ciaccio
Dott. Mario Antonelli
Dott. Roberto Di Nardo

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"It's about understanding! Understanding the world!"
P. Higgs

"La pratica genera abilità!"
L.B.

"Homo sum, nihil humani ad me alienum puto"
Terenzio

*"Du' pacchi de rigatoni tra i maglioni nella borsa, lí pe' damme forza, che
quassú é tutta 'na corsa!"*
C.R.

a Lorenzo

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Introduzione

Il bosone di Higgs è una particella unica nel Modello Standard; è una particella scalare e non è mediatore di alcuna forza, sebbene la sua esistenza sia fondamentale per spiegare la natura massiva della materia e rendere la teoria rinormalizzabile.

Le prime misure effettuate durante il Run1 al Large Hadron Collider (LHC) hanno consentito di scoprire il bosone di Higgs avente una massa di circa 125 GeV e di effettuare le prime misure delle sue proprietà. Nel Modello Standard (MS) la massa dell'Higgs è un parametro libero ma, una volta nota, la sezione d'urto di produzione e le frazioni di decadimento possono essere precisamente calcolate. Proprio per questo, misure di precisione delle proprietà della nuova particella sono importanti al fine di esplorare potenziali deviazioni dalle predizioni del MS.

Ad LHC, la produzione inclusiva del bosone di Higgs è dominata dalla fusione tra gluoni (ggF), seguita in ordine di sezione d'urto dalla fusione tra bosoni vettori (VBF) e produzione associata dell'Higgs con bosoni vettori, anche detta Higgs-Strahlung (VH).

I primi risultati sulle proprietà dell'Higgs mostrano che la risonanza osservata a 125 GeV è consistente con una particella $J^P = 0^+$, ipotesi alternative sono state escluse ad un livello di confidenza migliore del 95%, e misure preliminari delle sue proprietà non hanno dato alcuna evidenza di discrepanze osservate rispetto alle predizioni del MS. La crescente energia nel centro di massa delle collisioni (che risulta in un aumento della sezione d'urto di produzione del bosone di Higgs) e l'aumento di luminosità integrata (che migliora il potere statistico dei risultati) saranno fondamentali nel corso del Run2 al fine di migliorare la precisione di questi studi.

I canali di decadimento più sensibili ad LHC sono: $H \rightarrow W^+W^-$, $H \rightarrow \gamma\gamma$ e $H \rightarrow ZZ^* \rightarrow 4\ell$.

Il mio lavoro di tesi riguarda le misure delle proprietà del bosone di Higgs effettuate tra il Run1 ed il Run2 nel canale di decadimento $H \rightarrow ZZ^* \rightarrow 4\ell$ con il rivelatore ATLAS ad LHC.

In questo canale di decadimento, un Higgs con massa ~ 125 GeV decade in due bosoni Z ; la presenza di un bosone Z reale nel decadimento, implica due leptoni isolati ad alto p_T nell'evento e con massa invariante del sistema di-leptonico di circa 91.2 GeV, insieme ad altri due leptoni isolati ad im-

pulso più basso, provenienti dalla Z virtuale. Questo canale di decadimento è inoltre detto *Golden Channel* per l'ottimo rapporto tra segnale ed eventi di fondo.

Nell'ambito del mio lavoro di tesi, ho direttamente partecipato alla misura delle sezioni d'urto differenziali nel Run1 ¹ ed alla misura degli accoppiamenti del bosone di Higgs a particelle del MS nel Run2 ². Infine, ho studiato anche la sensitività a parametri di Teorie di Campo Effettivo (EFT) considerando tutta la statistica disponibile in Run2.

I risultati sono mostrati usando i dati raccolti in Run1 e Run2 rispettivamente a $\sqrt{s} = 8$ TeV e $\sqrt{s} = 13$ TeV che equivalgono ad una luminosità integrata pari a 20.7 fb^{-1} e 14.8 fb^{-1} .

Nel Capitolo 1 è presentato il meccanismo di Higgs nel Modello Standard da un punto di vista teorico, insieme a possibili interpretazioni Oltre il Modello Standard (BSM) nel settore dell'Higgs. Sono descritti i modi di produzione e decadimento rilevanti ad LHC e si fornisce un riassunto delle misure effettuate durante il Run1 per dare una visione d'insieme del contesto in cui si inserisce il mio lavoro di tesi.

Il Capitolo 2 riguarda l'esperimento ATLAS; la sua struttura è presentata e l'Inner Detector, i Calorimetri, lo Spettrometro a Muoni ed il Trigger sono descritti con maggiore dettaglio. Le caratteristiche di identificazione e ricostruzione per muoni ed elettroni sono inoltre riportate alla fine di questo Capitolo, con attenzione al loro ruolo nell'analisi.

Nel Capitolo 3 sono descritte la selezione degli eventi e l'analisi nel canale di decadimento dell'Higgs in due bosoni Z che successivamente decadono in 2 leptoni.

Il Capitolo 4 mostra le misure, effettuate con 20.3 fb^{-1} ad $\sqrt{s} = 8$ TeV, delle sezioni d'urto fiduciali inclusive e differenziali. Particolare attenzione è posta sulle misure delle dipendenze della sezione d'urto ad un determinato set di variabili. Sono proprio queste misure che permettono di aumentare la sensibilità ai rapporti di produzione dell'Higgs, ai numeri quantici di spin/ $\mathcal{CP}$, a studi perturbativi di QCD, a sondare le PDF (funzioni di distribuzione dei partoni). Gli studi sono effettuati definendo una regione fiduciale vicina a quella ricostruita, al fine di arginare possibili dipendenze dal modello e le misure sono state ottenute in bin delle variabili di interesse.

Il Capitolo 5 descrive la misura degli accoppiamenti del bosone di Higgs a particelle del MS, effettuate con 14.8 fb^{-1} ad $\sqrt{s} = 13$ TeV. La misura è data suddividendo gli eventi in categorie costruite in base alla caratteristica dell'evento, al fine di discriminare tra i modi di produzione dell'Higgs. Nel MS, il bosone di Higgs è una particella scalare con $\mathcal{CP}$ -pari ($J^{\mathcal{CP}} = 0^{++}$). Teorie di fisica BSM spesso contemplano un settore di Higgs esteso, con

¹Presentazione per l'Open Reading dell'articolo relativo all'analisi: indico.cern.ch/event/327318/ (G.Mancini)

²Presentazione per l'Approval dell'analisi: indico.cern.ch/event/558379/ (G.Mancini)

diversi bosoni di Higgs neutri; tali casi, possono anche includere stati di $\mathcal{CP}$ -misto nelle interazioni del bosone di Higgs, che possono risultare in differenze osservabili nella cinematica delle particelle nello stato finale dei loro decadimenti, o dalla produzione dell'Higgs (come nel caso delle interazioni via VBF). La possibile presenza di termini BSM nella Lagrangiana che descrive la risonanza a spin-0 viene investigata descrivendo l'interazione nel vertice HVV in termini di operatori di campo effettivo $\mathcal{CP}$ -pari e $\mathcal{CP}$ -dispari e ponendo limiti sulle corrispondenti costanti di accoppiamento.

Il Capitolo 6 infine, mostra uno studio di sensitività ottenuto mediante una parametrizzazione di tipo EFT generale, usando Pseudo Osservabili (POs) definiti nello stato finale $2e2\mu$ con tutta la statistica che si attende per il Run2.

Introduction

The Higgs Boson is the keystone particle of the Standard Model (SM): its existence explains the massive nature of matter and makes the theory renormalizable.

The first measurements performed during the Run 1 at the Large Hadron Collider (LHC) allowed for the discovery of the Higgs boson with a mass around 125 GeV and the first measurements of its properties.

While in the SM its mass (m_H) is a free parameter, the production cross sections and decay branching ratios (BR) of the Higgs boson can be precisely calculated once the mass is known. Therefore, precision measurements of the properties of the new particle are important to explore potential deviations from SM predictions. At the LHC, the Higgs inclusive production is dominated by the gluon fusion (ggF) process, followed by Higgs boson production in the vector-boson fusion (VBF) and the vector-boson associated production (VH) mechanisms, the so called "Higgs Strahlung".

The first results of Higgs properties measurements show that the 125 GeV resonance is consistent with a particle $J^P = 0^+$, alternative hypotheses have been excluded with a $C.L. > 95\%$, and preliminary measurements of its properties have not given any evidence of discrepancies with respect to the SM predictions. The increasing energy of the collisions (resulting in an enhancement of the production cross section for the Higgs Boson) and the increasing luminosity (improving the statistical power of the results) will be fundamental during Run2 in order to improve the accuracy of such tests.

The most sensitive decay channels at LHC are the $H \rightarrow W^+W^-$, $H \rightarrow \gamma\gamma$ and the $H \rightarrow ZZ^* \rightarrow 4\ell$.

My thesis's work concerns the measurements of the Higgs boson properties performed across Run1 and Run2 in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with the ATLAS detector at the LHC. An Higgs with mass around 125 GeV, decays in an on-shell Z boson and an off-shell one. The presence of an on-shell Z provides two high p_T leptons in the final state, a clear signature for the trigger, together with other two leptons coming from the decay of the off-shell Z , that help in the signal identification. This decay channel $H \rightarrow ZZ^* \rightarrow 4\ell$ is also referred to as the *Golden Channel* due to the good signal over background ratio.

I directly participated to the differential cross section measurements in Run1

³ and to the measurements of the couplings of the Higgs boson to SM particles in Run2 ⁴. Finally, I have also studied the sensitivity to parameters of Effective Field Theory (EFT) with the full Run2 data set.

The results are given both using the Run1 and Run2 data sample collected respectively at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 20.7 fb^{-1} and 14.8 fb^{-1} .

In Chapter 1 the Higgs mechanism in the Standard Model scenario is presented from a theoretical point of view together with possible Beyond Standard Model (BSM) interpretations within the Higgs sector. The production and decay modes relevant at LHC are described and a summary of the measurements performed during Run1 is given to give a picture of the state of the art in which this work has been part.

Chapter 2 deals with the ATLAS experiment; its structure is presented and the Inner Detector, Calorimeters, Muon Spectrometer and Trigger are described more in details. The identification and reconstruction performances for muons and electrons are also reported at the end of this Chapter, focusing on their role for the analysis.

In Chapter 3 the event selection and the cut based analysis are described, the decay channel of the Higgs in two Z bosons which subsequently decay in 2 leptons each.

In Chapter 4 the fiducial inclusive and differential cross section measurements are shown. Particular attention is posed on the study of the measurements of the cross section dependence on a set of selected variables. The measurements allows to improve the sensitivity to the Higgs boson production mode rates, spin/ $\mathcal{CP}$ quantum numbers, to test perturbative QCD predictions, probe the proton parton distribution functions (PDF). Studies are performed defining a fiducial region close to the reconstructed one, to prevent model dependencies and measurements have been performed in bins of the variables of interest.

Chapter 5 deals with the measurements of the Higgs boson coupling to SM particles; the measurement is performed dividing the events in categories built depending on the characteristic of the event, aiming for discrimination between production modes. In the SM, the Higgs boson is a $\mathcal{CP}$ -even scalar particle ($J^{\mathcal{CP}} = 0^{++}$) and theories of physics BSM often require an extended Higgs sector featuring several neutral Higgs bosons. Such cases may include $\mathcal{CP}$ -mixing in the Higgs boson interactions, which could result in observable differences in the kinematics of final-state particles produced in their decays, or from Higgs boson production, such as in VBF interactions. The possible presence of BSM terms in the Lagrangian describing the spin-0 resonance is investigated describing the HVV vertex interaction in terms of an effective BSM $\mathcal{CP}$ -odd and $\mathcal{CP}$ -even operators and deriving limits on the correspond-

³Presentation for the Open Reading: indico.cern.ch/event/327318/ (G.Mancini)

⁴Presentation for the Approval: indico.cern.ch/event/558379/ (G.Mancini)

ing BSM tensor couplings are derived.

Finally, Chapter 6 shows a sensitivity study performed on a general EFT parametrization using Pseudo Observables (POs) defined in the $2e2\mu$ final state with the full statistics available in Run2.

Chapter 1

The Standard Model and the Higgs Boson

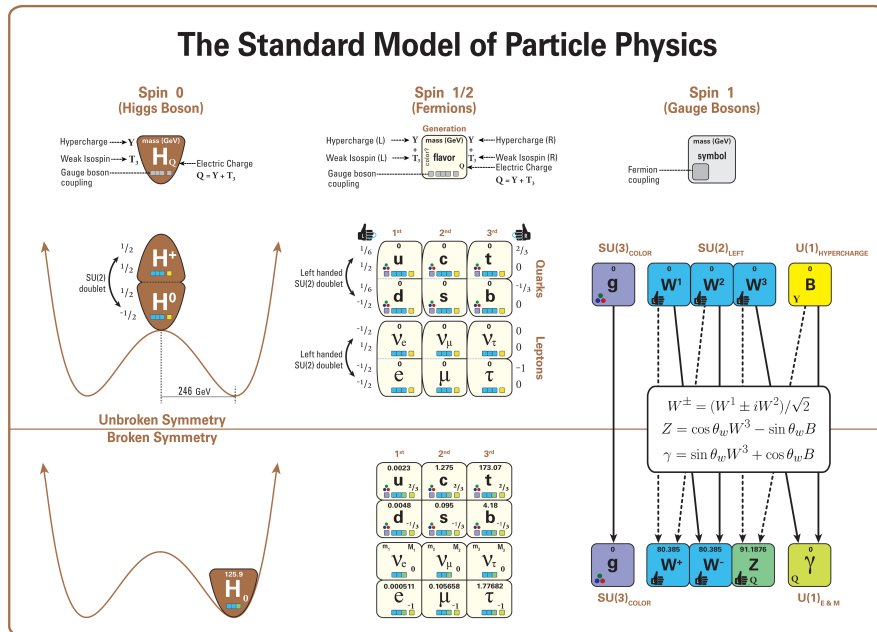


Figure 1.1: The elementary particles of the Standard Model: the crucial role of the Higgs boson in electroweak symmetry breaking.

The Standard Model describes three out of the four fundamental interactions in a coherent Quantum Field Theory framework:

- the electromagnetic interaction;
- the weak interaction;
- the strong interaction.

It describes the elementary particles (Figure 1.2), divided into:

- fermions (leptons and quarks) which are part of the ordinary matter,
- bosons which mediate the fundamental interactions (photons in case of electromagnetic interaction; W^+ , W^- and Z^0 for the weak interaction; gluons for the strong interaction) and the Higgs boson which explains the massive nature of the particles within the SM.

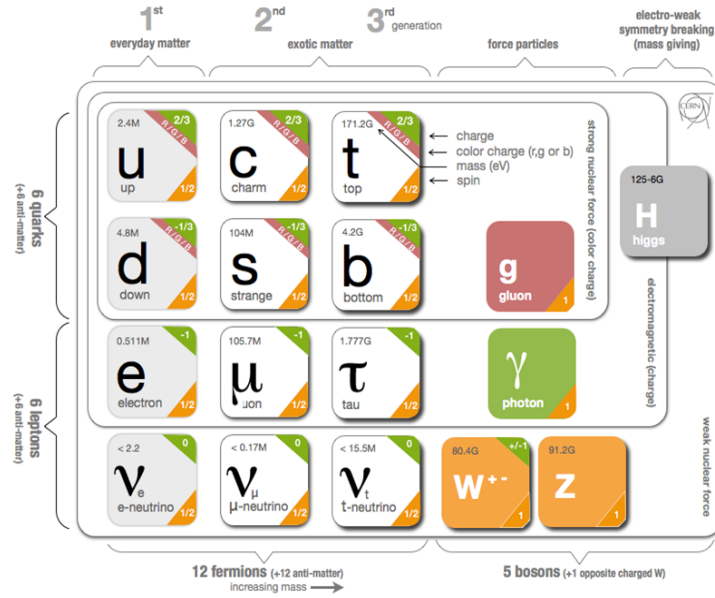


Figure 1.2: The elementary particles of the Standard Model.

The Standard Model (SM) was originally developed in the 1960s by Glashow, Weinberg and Salam and it has been a very successful theory since it provides predictions and explains most of the results of the experiments in particle physics up to the energies explored at LEP ($\mathcal{O}(10^2 \text{ GeV})$) and Tevatron ($\mathcal{O}(1 \text{ TeV})$).

The Higgs boson is the keystone particle of the Standard Model; its existence is fundamental in order to explain the massive nature of matter and W and Z bosons, and to make the SM re-normalizable. The Higgs is a scalar

boson and it does not carry any force; it has been hunted for decades, but never found until July 4th 2012 when the ATLAS and CMS experiments both announced the discovery of an Higgs-like resonance with a mass of ~ 125 GeV at the LHC $p - p$ collider [1] [2].

On a mathematical point of view, the SM is a gauge field theory based on the symmetries of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ group, where the interactions are generated from the requirement of local gauge invariance. The subgroup $SU(2)_L \times U(1)_Y$ is the core of the SM, describing QED and weak interactions as a whole: the electroweak interaction.

On the other side, $SU(3)_C$ is an almost straight forward extension for QCD interactions of the QED formalism given by the $U(1)_{e.m.}$ group.

1.1 Electroweak Theory

The electroweak unification was formalized in the 1960s by Glashow, Weinberg and Salam and, before being unified with the electromagnetic one. The electromagnetic interaction had been described by Fermi, who assumed, in analogy with the electrodynamics, a point-like interaction with G_F being the coupling between the four fermions involved: $G_F/(\hbar c)^3 = (1,16637 \pm 0,00002)10^{-5} \text{ GeV}^{-2}$ [6]).

The electroweak theory (EW), reveals its limits when applied at high energies, where divergences arise, in fact, it is a non-abelian theory since it implies self-interaction vertices with three and four gauge bosons (Figure 1.3).

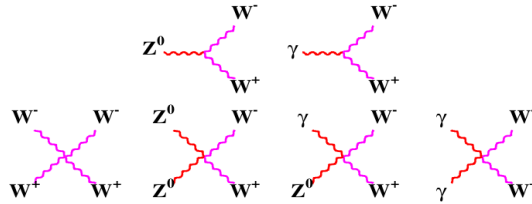


Figure 1.3: Feynman diagrams showing the self-coupling between gauge bosons.

Considering the following process (Figure 1.4):

$$e^+ e^- \rightarrow W^+ W^- \quad (1.1)$$

we can notice that, without the contribution of the diagram of the Z exchange, the cross section diverges at high energies, confirming the non-abelianity of the theory (Figure 1.5).

The interactions mediated by the two W vector bosons are known as weak Charge Current (CC) interactions, those mediated by the Z are known

as weak Neutral Current (NC) interactions and they don't involve charge-changing processes.

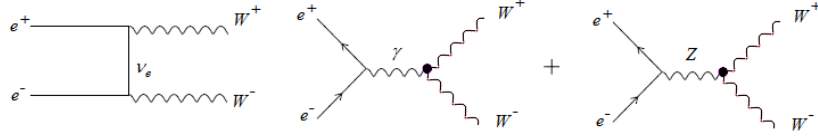


Figure 1.4: Feynman diagrams for the different contributions to the reaction $e^+e^- \rightarrow W^+W^-$ process.

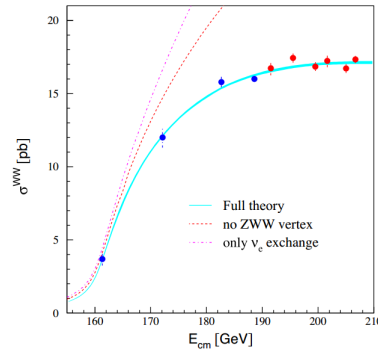


Figure 1.5: Cross section for the $e^+e^- \rightarrow W^+W^-$ process adding or not the contribution of the Z exchange.

In the limit of $q^2 \ll m_W^2$, where q is the transferred momentum in the reaction, a relation can be established between the weak coupling constant (g_W) and the Fermi coupling constant (G_F):

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} \quad (1.2)$$

The electroweak interaction is a gauge theory described by the $SU(2)_L \times U(1)_Y$ symmetry group where the subscript “L” came from the observation that only left-handed particles are coupled to CC.

The EW theory is also called $V-A$ because it couples particles which are Vectors to those which are Axial Vectors. The $SU(2)_L$ group represents the idea based on the observation that weak CC interactions couple pair of particles like:

- electron and muons to ν_e and ν_μ respectively;
- $p \rightarrow n$ e ν_e in interactions like β decays;

- $\nu_\mu N \rightarrow \mu X$ in neutrino scatterings.

This means that weak CC are formalized as follows:

$$j_\mu^+ = \bar{\nu}\gamma_\mu \frac{1}{2}(1 - \gamma^5)e = \bar{\nu}_L\gamma_\mu e_L \quad j_\mu^- = \bar{e}\gamma_\mu \frac{1}{2}(1 - \gamma^5)\nu = \bar{e}_L\gamma_\mu \nu_L \quad (1.3)$$

where $\frac{1}{2}(1 - \gamma^5)$ is the chiral left projector which makes the interaction effective only between left-handed particles and thus introduces the maximum parity violation in weak interactions.

For example the matrix element, whose square is proportional to the cross section of the reaction, in case of the β decay takes this form:

$$M = \frac{g_W}{\sqrt{2}} \left(\bar{u}_p \frac{\gamma_\mu}{2} (1 - \gamma^5) u_n \right) \left(\bar{u}_e \frac{\gamma_\mu}{2} (1 - \gamma^5) u_\nu \right) \quad (1.4)$$

Since only left-handed particles and right-handed antiparticles participate in the weak interaction, it comes out that left-handed fermions are $SU(2)$ doublets, while right-handed fermions are singlets of $SU(2)$.

$$\begin{pmatrix} \nu_L^e \\ e_L^- \end{pmatrix} \quad \begin{pmatrix} \nu_L^\mu \\ \mu_L^- \end{pmatrix} \quad \begin{pmatrix} \nu_L^\tau \\ \tau_L^- \end{pmatrix} \\ (e_R^-) \quad (\mu_R^-) \quad (\tau_R^-) \quad (1.5)$$

The Right-handed neutrino singlet is not observed in nature.

Using the Pauli matrices (σ_i) which are the fundamental representation of $SU(2)$, we may rewrite the CCs as:

$$(j^\pm)_\mu = \bar{\psi}_L \gamma_\mu \sigma_\pm \psi_L \quad (1.6)$$

where $\sigma_\pm$ are operators that change the state of the particle within the $SU(2)_L$ doublet. Those operators, $\sigma_\pm$, are identified as generators of the weak isospin and they assume the following form:

$$\sigma_\pm = \frac{1}{2}(\sigma_1 \pm i\sigma_2) \quad (1.7)$$

The W bosons couple leptons between the same doublet with a coupling constant which is equal to $g_W/\sqrt{2}$, being

$$g_W \sin \theta_W = g' \cos \theta_W = e \quad m_W = m_Z \cos \theta_W \quad (1.8)$$

where θ_W is the Weinberg angle, which describes the electroweak interference between the photon field and the neutral weak boson field, and can be estimated from the previous relations.

The third component of the $SU(2)_L$ representation (σ_3), can be used to define a new current, orthogonal to the previous two:

$$(j^3)_\mu = \bar{\psi}_L \gamma_\mu \frac{\sigma_3}{2} \psi_L \quad (1.9)$$

where $\sigma_3/2$ defines the third generator of the weak isospin (T_3).

This charge-preserving current cannot be identified with the weak NC since it has been experimentally observed to have both left and right-handed terms while j_μ^3 couples only to left-handed particles. The identification of a triplet of currents forms the basis for the gauge theory of weak interactions.

The simplest unification of the parity violating weak force and the parity conserving electromagnetic force is the $SU(2)_L \times U(1)_Y$ gauge theory, that provides two weak CCs and two NCs. Among the two NCs, one violates the parity while the other couples to both left and right-handed particles.

Local gauge invariance under $SU(2)$ transformations requires the introduction of three massless and spin 1 gauge bosons W_i where i runs from one to three and an additional spin 1 gauge boson B_μ which couples to both the right-handed and the left-handed components. W^+ and W^- are then linear combinations of W_1 and W_2 , while A_μ (the photon field) and Z^0 are linear combination of B_μ and W_3 .

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (1.10)$$

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$$

In the $SU(2)$ symmetry, the conserved quantity is the weak isospin (T_i with $i = 1, 2, 3$).

Combining the $SU(2)_L$ weak isospin group with $U(1)_{e.m.}$ electromagnetic group, as suggested by Glashow, the electroweak unification is obtained, with the electromagnetic interaction being included in the EW theory.

$U(1)_Y$ is an independent gauge symmetry whose generator is the weak hypercharge (Y):

$$Y = Q - T_3 \quad (1.11)$$

where Q is the electric charge and T_3 the third component of the weak isospin.

Local $SU(2)_L \times U(1)_Y$ gauge invariance forbids massive gauge bosons

In the theory of Quantum ElectroDynamics (QED) the requirement of local gauge invariance, i.e. the invariance of the Lagrangian under the transformation $\phi' \rightarrow e^{i\alpha(x)}\phi$ on scalar fields plays a fundamental role.

Invariance is achieved by replacing the partial derivative by a covariant derivative, $\partial_\mu \rightarrow D_\mu = \partial_\mu + ieA_\mu$ and introducing a new vector field A with very specific transformation properties: $A'_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu\alpha$.

The Lagrangian for a free particle then becomes:

$$\mathcal{L}_{QED} = \mathcal{L}_{free} + \mathcal{L}_{int} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.12)$$

which not only describes the presence of a vector field in nature (the photon), but also automatically yields an interaction term $L_{int} = eJ^\mu A_\mu$ between the vector field and the particle. Under these symmetry requirements it is unfortunately not possible for a gauge boson to acquire a mass. In QED for example, a mass term for the photon, would not be allowed as such a term breaks the gauge invariance:

$$\frac{1}{2}m_\gamma^2 A_\mu A^\mu = \frac{1}{2}m_\gamma^2 (A_\mu + \frac{1}{e}\partial_\mu \alpha)(A^\mu + \frac{1}{e}\partial^\mu \alpha) \neq \frac{1}{2}m_\gamma^2 A_\mu A^\mu \quad (1.13)$$

This example holds only for $U(1)$, nevertheless a similar argument holds in the electroweak model for the W and Z bosons, particles that we know are massive and make the weak force only relevant at very small distances.

Local $SU(2)_L \times U(1)_Y$ gauge invariance forbids massive fermions

The gauge invariant Lagrangian which describes the electroweak interactions is therefore:

$$\mathcal{L} = -\frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{\phi}i\gamma^\mu D_\mu \phi \quad (1.14)$$

where the field tensors $W_{\mu\nu}$ and $B_{\mu\nu}$ are defined as follows, and D_μ is the covariant derivative:

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g_W \epsilon_{ijk} W_\mu^j W_\nu^k \quad (1.15)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (1.16)$$

$$D_\mu = \partial_\mu + ig_W W_\mu^a T_a + ig' \frac{1}{2} B_\mu Y \quad (1.17)$$

In the previous formulas g_W is the $SU(2)$ coupling constant and g' the $U(1)$ coupling constant.

Similarly as in QED, invariance under local gauge transformations in the electroweak model requires introducing a weak current, J^{weak} and a different transformation for isospin singlets and doublets.

A mass term for a fermion in the Lagrangian would be of the form $-m_f \bar{\psi}\psi$, but such terms in the Lagrangian are not allowed as they are not gauge invariant. This is clear when we decompose the expression in helicity states:

$$-m_f \bar{\psi}\psi = -m_f (\bar{\psi}_R + \bar{\psi}_L)(\psi_L + \psi_R) = -m_f [\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R], \quad \bar{\psi}_R \psi_R = \bar{\psi}_L \psi_L = 0 \quad (1.18)$$

Since ψ_L (left-handed, member of an isospin doublet, $I = 1$) and ψ_R (right-handed, isospin singlet, $I = 0$) behave differently under rotations of $SU(2)_L \times U(1)_Y$, these terms are not gauge invariant:

$$\psi_L \rightarrow \psi'_L = e^{i\alpha(x)T + i\beta(x)Y} \psi_L \quad \psi'_R \rightarrow \psi'_R = e^{i\beta(x)Y} \psi_R \quad (1.19)$$

Finally, the interaction between fermions and the gauge fields is expressed by the following expression:

$$\mathcal{L} = -\overline{\phi}_L \gamma^\mu \left(\frac{g_W}{2} W_\mu^a T_a + \frac{g'}{2} B_\mu Y \right) \phi_L - \overline{\phi}_R \gamma^\mu \left(\frac{g'}{2} B_\mu Y \right) \phi_R \quad (1.20)$$

It is therefore clear that, in order to preserve the local $SU(2)_L \times U(1)_Y$ gauge invariance, mass terms for fermions and bosons cannot be directly introduced in the Lagrangian and the so called Unitarity Violation arises as the energy increases.

Unitarity violation

Fermi's theory of weak interactions leads to the unitarity violation at the electroweak scale ($s \sim G_F$), due to the assumption of point-like interactions; the introduction of the massive intermediate vector bosons moves this problem to higher energies.

The calculation of the scattering cross section for longitudinally polarized $W^\pm$ and Z bosons (WW -scattering shown in Figure 1.6) violate unitarity at high energy as $\sigma_{WW \rightarrow ZZ} \propto E^2$: such an energy dependency clearly makes the theory non-renormalizable.

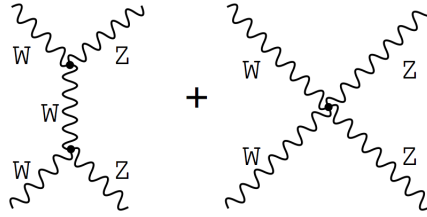


Figure 1.6: Feynman diagrams for the different contributions to the $W^+W^- \rightarrow ZZ$ process

This problem can be solved adding two new diagrams, which take into account the interaction between the weak vector bosons and the Higgs boson: implying the Higgs boson mass to be $m_H < 1$ TeV (Figure 1.7).

1.1.1 The Higgs mechanism: a possible way out

The idea of *spontaneous symmetry breaking of a local gauge invariant theory*, known as the *Higgs mechanism*, was proposed in 1962 by Philip Warren Anderson, following works in the late 1950s on symmetry breaking in superconductivity and a 1960 paper by Yoichiro Nambu that discussed its application within particle physics.

The idea was to introduce a new field with a very specific potential that keeps the full Lagrangian invariant under $SU(2)_L \times U(1)_Y$, but will make

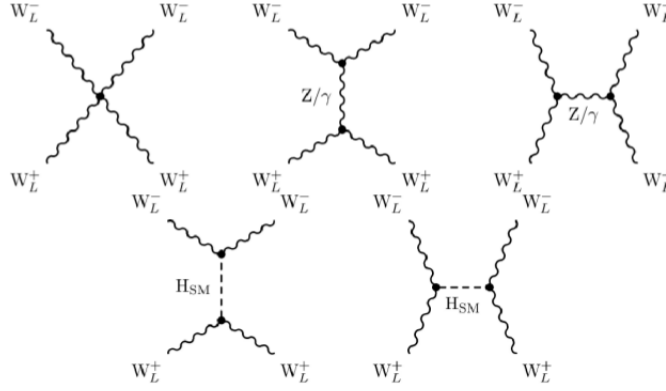


Figure 1.7: The upper three diagrams violate unitarity starting from $\sqrt{s} = 1.2$ TeV. The interaction of weak bosons with the Higgs prevents the violation of unitarity in the cross section of the reaction $W^+W^- \rightarrow W^+W^-$.

the vacuum not invariant under this symmetry.

A theory able to finally explain mass generation without “breaking” gauge theory was then published almost simultaneously by two independent groups in 1964: Robert Brout, François Englert and Peter Higgs [7]; Gerald Guralnik, C. R. Hagen, and Tom Kibble [8].

Weinberg and Salam contributed to the development of the Standard Model by extending the ABEGHHK’tH mechanism ¹ to the non-abelian $SU(2)_L \times U(1)_Y$ group.

On this purpose, they conjectured that the four massless gauge bosons of weak interactions get their mass interacting with a scalar field, resulting in a single massless gauge boson (the photon) and three massive gauge bosons ($W^\pm$ and Z).

This is possible because the Higgs field has a potential function which has a peculiar shape known as the “*Mexican hat*” that allows degenerate vacuum solutions with a non-zero vacuum expectation value (v) (Figure 1.8).

The Higgs boson is then responsible for the spontaneous electroweak symmetry breaking, gives mass to the vector bosons of weak interaction, and makes the theory re-normalizable.

In the context of the $SU(2)_L \times U(1)_Y$ symmetry, the Higgs mechanism is implemented through an additional $SU(2)_L$ doublet of complex scalar fields (four real scalar fields):

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

¹for Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and ’t Hooft, usually known as the Higgs mechanism

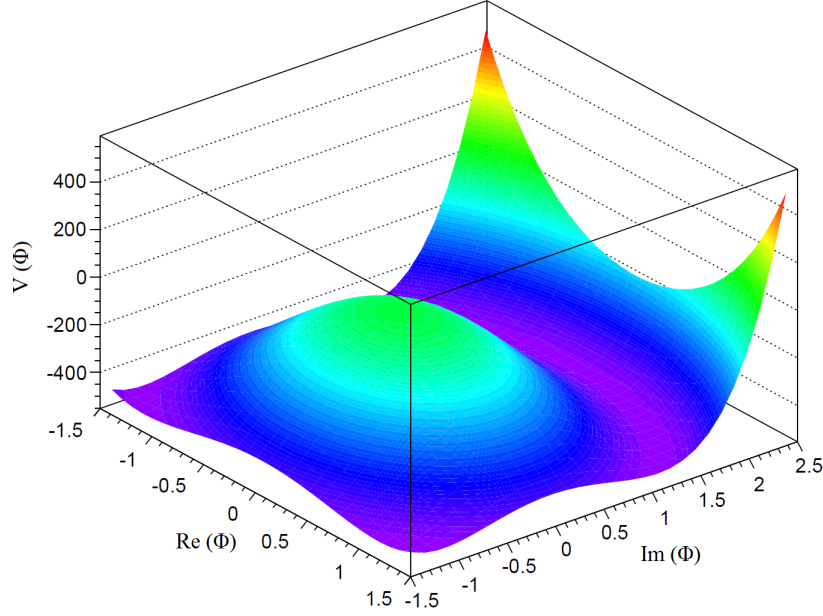


Figure 1.8: The Higgs potential with its non-zero expectation value and its shape known as the “mexican hat”; the units on the axis are completely arbitrary.

The Higgs contribution to the electroweak Lagrangian is:

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 |\phi|^2 - \lambda |\phi|^4 \quad (1.21)$$

where D_μ is the covariant derivative associated to $SU(2)_L \times U(1)_Y$, the potential is parametrized by λ and μ and it is chosen to be an even function of the scalar field, so that the Lagrangian is invariant under the parity transformation ($\phi \rightarrow -\phi$).

Adding the Higgs scalar field ϕ to the electroweak Lagrangian gives:

$$\begin{aligned} \mathcal{L}_\phi = & \left[\frac{1}{2} (\partial_\mu H^2) - \lambda v^2 H^2 \right] + \frac{1}{8} g_W^2 v^2 (W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) + \\ & + \frac{1}{8} (g_W W_\mu^3 - g' B_\mu) (g_W W^{3\mu} - g' B^\mu) + \\ & + \text{kinetic terms for } W \text{ and } B + \text{higher order terms} \end{aligned} \quad (1.22)$$

where $\mu^2 < 0$, $\lambda > 0$ and H is the massive scalar field.

λ is the strength of the quartic self-coupling of the scalar field (showed by $|\phi|^4$ term) and it is required to be positive so that the energy is bounded from below; this requirement ensures the existence of stable ground states. The parameter μ can be studied in two qualitatively different cases (Figure 1.9).

If $\mu^2 > 0$, the potential has a unique minimum at $\phi = 0$ that corresponds to

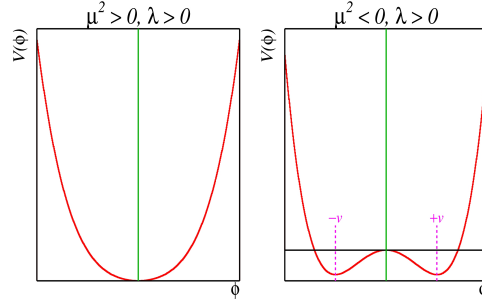


Figure 1.9: The differences in the Higgs potential due to the sign of μ^2 are shown. (left) The case of $\mu^2 > 0$ is reported. (right) The case of $\mu^2 < 0$ is shown: the degeneracy of the vacuum state is represented by $+v$ and $-v$ which are the states of minimum energy for the Higgs potential.

the ground state, i.e. the vacuum. In terms of quantum field theory this means that the field ϕ has zero vacuum expectation value and $\mathcal{L}_\phi$ is the Lagrangian for a scalar particle of mass μ and massless gauge bosons.

If $\mu^2 < 0$, the Lagrangian has a mass term of the negative sign for the field ϕ and the minimum energy is not at $\phi = 0$; the potential assumes the “*Mexican hat*” shape, with $\phi = 0$ being a local maximum.

Choosing one of the non-zero ground states spontaneously breaks the $SU(2)_L \times U(1)_Y$ symmetry because the ground state is no more symmetric under $SU(2)_L \times U(1)_Y$.

The minimum of this potential no longer corresponds to a unique value of ϕ but there is an infinite number of states where the real fields ξ_1 , ξ_2 , ξ_3 and H have a zero vacuum expectation value; this gives rise to a scalar field $H(x)$, the massive Higgs field, and to three massless scalar fields $\xi_a(x)$, the Goldstone bosons.

The former describes radial excitations from the ground state changing the potential energy while the latter correspond to angular excitations without potential energy change; these three massless scalar bosons correspond to the three broken symmetry generators.

In the Lagrangian $\mathcal{L}_\phi$ (equation 1.22), the first term describes the massive scalar field H , where $m_H = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}$; the second term refers to the mass terms of W^1 and W^2 gauge fields (may be combined in order to give the $W^\pm$ bosons) whose mass is found to be $m_W = \frac{1}{2}g_W v$; in the third term the gauge boson fields $(W^3)_\mu$ and B_μ are mixed into one mass term, confirming that their mixture give rise to two new vector gauge bosons: Z_0 and the photon.

The parameters introduced by the Glashow-Weinberg-Salam model are then just four: the coupling constants g_W and g' and the Higgs potential parameters λ and v , where $v^2 = \frac{-\mu^2}{\lambda}$.

Rather than these theoretical values, for convenience, other four values associated with experimental observables, are commonly used as parameters of the Standard Model: the fine-structure constant α , the Fermi coupling constant G_F , the Z boson mass and the Higgs boson mass:

$$\alpha = \frac{1}{4\pi}(g_W)^2 \sin^2 \theta_W \quad G_F = \frac{1}{v^2 \sqrt{2}} \quad (1.23)$$

The first three parameters are measured with great precision, the last parameter, the mass of the Higgs boson, is going to be measured with great precision since its discovery in July 4th 2012: the current estimation being $m_H = (125.09 \pm 0.21(stat.) \pm 0.11(syst.))$ GeV from latest results obtained combining the most sensitive channels from the ATLAS and CMS experiments [5].

1.2 Standard Model Higgs and opened scenarios

The Standard Model does not provide a prediction for the Higgs Boson mass since it is a free parameter of the theory, but it gives predictions on the possible mass values. These constraints can be derived using theoretical arguments based on the energy regime in which the perturbative expansion of the Standard Model is valid.

Although these argumentations come from very reasonable considerations (unitarity in longitudinal scattering amplitudes, perturbativity of the Higgs self-coupling and stability of the electroweak vacuum), they cannot provide stringent limits since they depend on the absence of New Physics up to a cut-off energy scale. This means that it can be set a range of masses that is valid as long as virtual effects of New Physics enter in the calculation of the Higgs boson mass.

1.2.1 Higgs Beyond the Standard Model

Despite the remarkable experimental confirmation of the Standard Model, it raises fundamental questions that it does not have the power to solve: it omits gravity, does not provide a candidate for dark matter, does not explain the matter-antimatter asymmetry in the universe, the neutrino masses.

These open questions make particle physicists believe that the Standard Model is only a simplification of a more complex underlying structure.

In the context of the Higgs boson physics, one of the main goal for the present and future searches is then to investigate the properties of the Higgs boson and to evaluate if we are dealing with the Standard Model Higgs boson or not and if there are hints of New Physics beyond the SM hidden, for example, in the Higgs sector.

There is anyway a barrier represented by the Higgs's decoupling theorem: if the spectrum of the Higgs sector contains one Higgs boson of mass m_h

and all other particles have a mass of at least M , then the influence of these particles on the properties of the light Higgs boson is proportional to m_h^2/M^2 and then, the effects of New Physics at 1 TeV on the properties of the Higgs are at the percent level. Precision measurements are therefore needed to see these corrections.

Proof of the theorem can be achieved integrating out the heavy fields. This gives a general Lagrangian with the Standard Model field content and $SU(2) \times U(1)$ symmetry. But, the Standard model is already the most general renormalizable model meeting these conditions. So, after we have measured the effective Standard Model parameters, the only effects of new fields come from dimension 6 operators, which give effects of size q^2/M^2 . In this context, the current 20 – 30% agreement of the Higgs properties with the predictions of the Standard Model is completely expected, but, more accurate measurements could potentially show deviations in all of the visible Higgs decay modes.

Since each Higgs coupling constant is guided by different types of New Physics in possible extensions of the SM, measurements on the Higgs couplings to SM particles are crucial in order to find possible hints of New Physics beyond the SM.

1.3 Overview of the measurements of the Higgs boson properties carried out by ATLAS and CMS at LHC during Run1

1.3.1 Higgs boson production at LHC

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

- gluon fusion production $gg \rightarrow H$ (Figure 1.10a): even if it is a loop induced production, it is the main production mode for the Higgs bosons at LHC collisions.
- vector boson fusion production $qq \rightarrow qqH$ (Figure 1.10b): has an order of magnitude smaller cross section; in this process the incoming quarks radiate electroweak bosons, which produce the Higgs boson and jets which can be observed in the forward directions. The Higgs boson decay products between the two jets, which are strongly separated in rapidity. This distinct signature can be used to strongly suppress many background processes.
- associated production with a W boson, $qq \rightarrow WH$ (Figure 1.11a), or with a Z boson, $pp \rightarrow ZH$, including a small ($\sim 8\%$) but less precisely

predicted contribution from $gg \rightarrow ZH$ ($ggZH$) (Figures 1.11a, 1.11b, and 1.11c);

- associated production with a pair of top quarks, $qq, gg \rightarrow ttH$ (Figure 1.12).

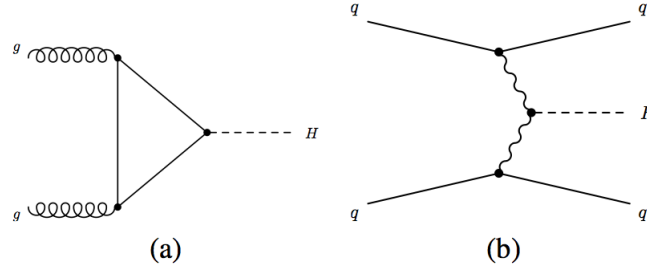


Figure 1.10: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) ggF and (b) VBF production processes.

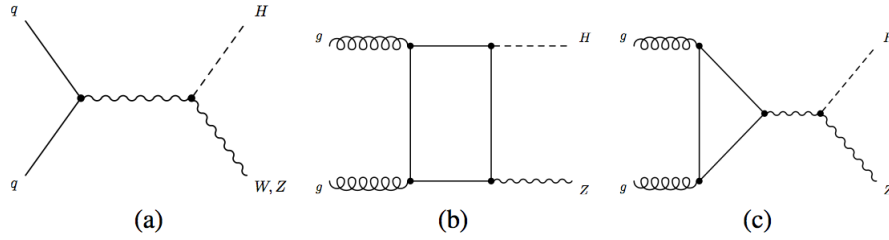


Figure 1.11: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) $qq \rightarrow VH$ and (b, c) $gg \rightarrow ZH$ production processes.

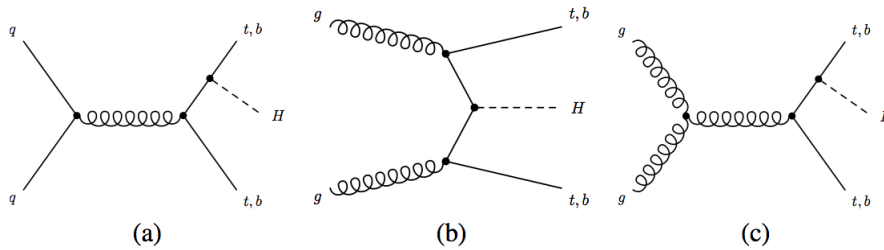


Figure 1.12: Examples of leading-order Feynman diagrams for Higgs boson production via the $qq/gg \rightarrow ttH$ and $qq/gg \rightarrow bbH$ processes.

Other less important production processes in the SM, which are not the target of a direct search, are $qq, gg \rightarrow bbH$ (bbH , Figure 1.12) and production

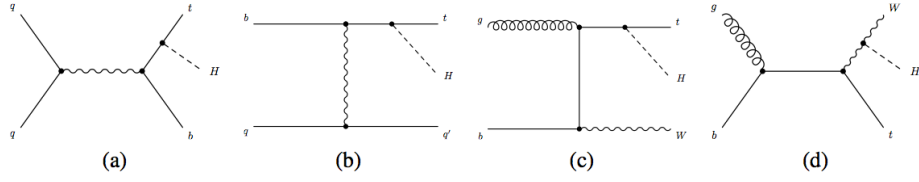


Figure 1.13: Examples of leading-order Feynman diagrams for Higgs boson production in association with a single top quark via the (a, b) tHq and (c, d) tHW production processes.

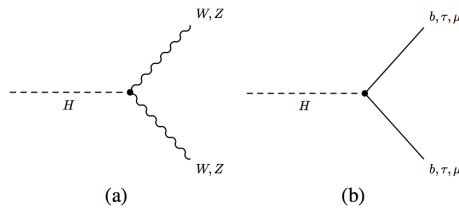


Figure 1.14: Examples of leading-order Feynman diagrams for Higgs boson decays (a) to W and Z bosons and (b) to fermions.

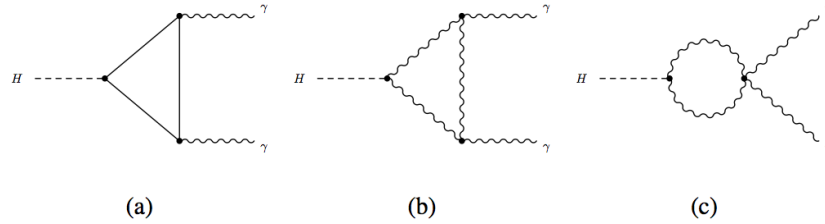


Figure 1.15: Examples of leading-order Feynman diagrams for Higgs boson decays to a pair of photons.

in association with a single top quark (tH), shown in Figure 1.13. The latter process proceeds through either $qq/q\bar{q} \rightarrow tHb/tHq$ (tHq) (Figures 1.13a and 1.13b) or $gb \rightarrow tHW$ (tHW) (Figures 1.13c and 1.13d) production.

Examples of leading-order (LO) Feynman diagrams for the Higgs boson decays considered in the combination are shown in Figures 1.14 and 1.15. The decays to W and Z bosons (Figure 1.14a) and to fermions (Figure 1.14b) proceed through tree-level processes whereas the $H \rightarrow \gamma\gamma$ decay is mediated by W boson or heavy quark loops (Figure 1.15).

Going from 8 to 13 TeV all the production cross sections scale by around a factor 2, but the ttH scales by almost a factor 4, (main backgrounds scale by a factor 2 too). The inclusive cross sections and branching fractions for the most important production and decay modes are summarised with their

overall uncertainties in Tables 1.1 and 1.16 and Figures 5.7 and 5.8 for a Higgs boson mass $m_H = 125.09$ GeV. The SM predictions of the branching

Table 1.1: Standard Model predictions for the Higgs boson production cross sections together with their theoretical uncertainties. The value of the Higgs boson mass is assumed to be $m_H = 125.09$ GeV [4]. The order of calculation is also reported.

Production process	Cross section [pb] $\pm$ QCD Scale Unc. [%] $\pm$ PDF+ α_S Unc. [%]		
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV
ggF $N^3\text{LO}+\text{NNLL}(\text{QCD})+\text{NLO}(\text{EW})$	$15.3^{+7.3}_{-7.9} \pm 3.2$	$19.4^{+7.3}_{-8.0} \pm 3.1$	$44.1^{+7.6}_{-8.1} \pm 3.1$
VBF $\text{NNLO}(\text{QCD})+\text{NLO}(\text{EW})$	$1.24 \pm 0.2 \pm 2.2$	$1.60 \pm 0.2 \pm 2.2$	$3.78^{+0.4}_{-0.3} \pm 2.1$
WH $\text{NNLO}(\text{QCD})+\text{NLO}(\text{EW})$	$0.576^{+0.7}_{-0.8} \pm 2.1$	$0.701^{+0.6}_{-0.8} \pm 2.0$	$1.37^{+0.5}_{-0.7} \pm 1.9$
ZH $\text{NNLO}(\text{QCD})+\text{NLO}(\text{EW})$	$0.338^{+2.6}_{-2.3} \pm 1.7$	$0.420^{+2.8}_{-2.4} \pm 1.7$	$0.882^{+3.8}_{-3.0} \pm 1.6$
ttH $\text{NLO}(\text{QCD})+\text{NLO}(\text{EW})$	$0.0886^{+3.5}_{-9.2} \pm 4.5$	$0.133^{+4.0}_{-9.2} \pm 4.3$	$0.507^{+5.8}_{-9.2} \pm 3.6$
bbH $5\text{FS}/\text{NNLO}(\text{QCD})+4\text{FS}/\text{NLO}(\text{QCD})$	$0.155^{+20.7}_{-22.5}$	$0.202^{+20.6}_{-22.4}$	$0.486^{+20.1}_{-23.9}$

Decay mode	Branching fraction [%]
$H \rightarrow bb$	57.5 ± 1.9
$H \rightarrow WW$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow cc$	2.90 ± 0.35
$H \rightarrow ZZ$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001

Figure 1.16: Standard Model predictions for the decay branching fractions of a Higgs boson with a mass of 125.09 GeV, together with their uncertainties. Included are decay modes that are either directly studied or important for the combination because of their contributions to the Higgs boson width.

fractions for $H \rightarrow gg$, cc , and $Z\gamma$ are included for completeness.

1.3.2 Higgs boson decay channels

Combined ATLAS and CMS measurements of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions have been performed by ATLAS and CMS during Run1 using the full dataset collected at LHC ($\sim 5 \text{ fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $\sim 20 \text{ fb}^{-1}$ at $\sqrt{s} = 8$ TeV) [5].

Run1 has been characterized by the Higgs boson discovery and the measure of its mass of about $m_H = 125$ GeV. Already within two to three years after the discovery, the Higgs boson production cross section and mass have been measured with a 15% and a 0.2% accuracy respectively.

During Run1, evidence of the Higgs boson have been found in the $H \rightarrow$

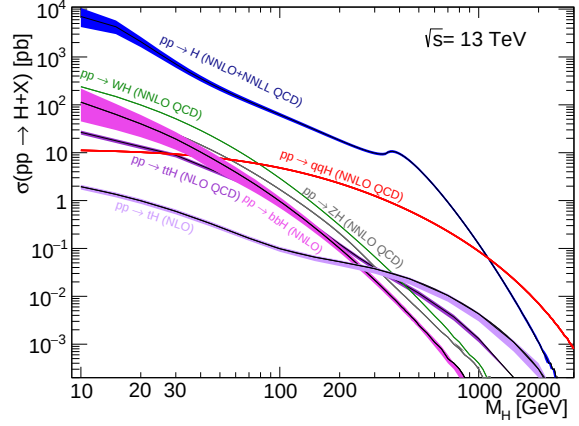


Figure 1.17: Standard Model Higgs boson production cross sections at $E_{CM} = 13$ TeV as a function of the Higgs boson mass.

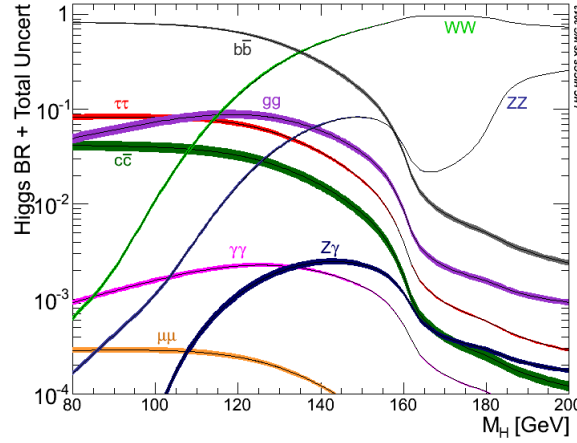


Figure 1.18: Standard Model Higgs boson decay branching ratios as a function of the Higgs boson mass.

$WW^* \rightarrow \ell\nu\ell\nu$, $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ which are the most sensitive channels, evidence has been found also in the $H \rightarrow \tau\tau$ and in the ggF and VBF production modes.

The Higgs boson branching ratios strongly vary with its mass, at the Higgs mass of 125 GeV, all the decays to bosons and to the heavier fermions provide large enough rates at the LHC. Some of the decays have overwhelming backgrounds or too small branching ratios to be observed with the Run1 LHC dataset. For this reason, there are mainly five decay channels which drive the Higgs boson measurements: the Higgs boson decays to a pair of b-quarks has the largest branching ratio, the second being the decay to pair of W-bosons. The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal is characterized by two isolated

leptons plus large missing energy due to the two undetected neutrinos, it has high statistics but also huge background.

The best mass resolution comes from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay signatures, which played a key role in the Higgs boson discovery. The $H \rightarrow \gamma\gamma$ channel is characterized by a narrow resonant signal peak above a large falling continuum background; the overall signal-to-background ratio is a few percent. The $H \rightarrow ZZ^* \rightarrow 4\ell$ channel suffers of very low statistics ($BR \sim 10^{-4}$) but has very little background, resulting in a signal-to-background ratio ~ 2 .

Finally, the decay to tau pairs gives good sensitivity for a leptonic decay mode. The main experimental signatures and strategies are driven by the decay modes. These decay channels are further divided into sub-channels to separate the different production modes and to increase the overall significance. As such, a large number of final states are investigated at the LHC: the Higgs boson signal has been independently observed by ATLAS and CMS experiments in almost every bosonic channel during Run1, Table 1.2 shows the significances reached in each decay channel using the Run1 dataset. The ATLAS and CMS detectors are based on different technolo-

Table 1.2: Observed (expected) Higgs signal significance in the main decay channels. Numbers marked with $\dagger$ assume $m_H = 125$ GeV.

Significance obs.(exp.)	ATLAS ($m_H = 125.36$ GeV)	CMS ($m_H = 125.6$ GeV)
$H \rightarrow \gamma\gamma$	5.2σ (4.6σ)	5.7σ (5.2σ)
$H \rightarrow ZZ^* \rightarrow 4\ell$	8.1σ (6.2σ)	6.8σ (6.7σ)
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	6.1σ (5.8σ)	4.3σ (5.8σ)
$H \rightarrow \tau\tau$	4.5σ (3.4σ)	3.2σ (3.7σ) $\dagger$
$H \rightarrow b\bar{b}$	1.4σ (2.6σ)	2.1σ (2.1σ) $\dagger$

gies requiring different reconstruction and calibration methods, and therefore, they are subject to different sources of systematic uncertainty. In the ATLAS design the emphasis was set on excellent jet and missing transverse momentum resolution, particle identification, and standalone muon measurement, while in CMS the emphasis was on excellent electron and photon resolution, and on good tracking (hence also muon) resolution.

In this section the main results performed during Run1 in the most sensitive channels will be shown: some of those will be deeper discussed in the following Chapters.

1.3.3 Higgs boson measurements at LHC during Run1

1.3.3.1 Higgs boson mass measurements

The Higgs boson mass measurement has been performed by both experiments in the channels with the best mass resolution, $H \rightarrow ZZ^* \rightarrow 4\ell$ and

$H \rightarrow \gamma\gamma$ which have a typical mass resolution of 1 – 2% [29].

The results are obtained from a simultaneous fit in the two channels and for the two experiments to obtain the combined measurement of the Higgs boson mass: $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV (Figures 1.19 and 1.20). The total uncertainty is dominated by the statistical term; the systematic uncertainties are dominated by effects related to the photon, electron, and muon energy or momentum scales and resolutions.

The measured masses from the individual channels and the two experiments are found to be consistent among themselves, therefore SM expectations for all the quantities are calculated at the combined mass value.

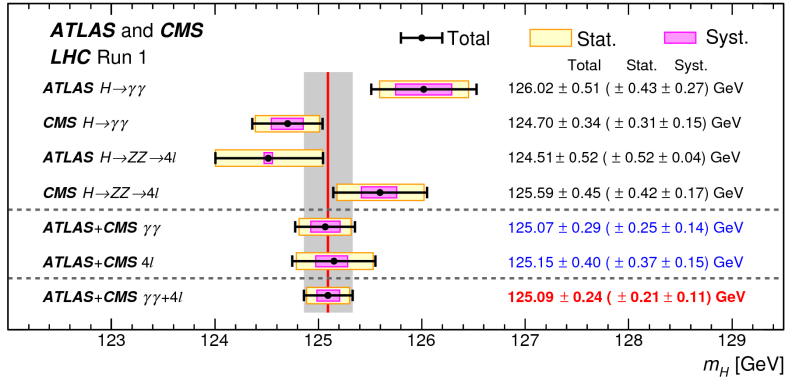


Figure 1.19: Measured values of the Higgs boson mass for the separated ATLAS and CMS $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels, as well as for the combined fit in each channel and altogether.

1.3.3.2 Parametrization of the signal yields

Signal strength

The signal strength parameter (μ) is defined for an observable as the ratio between the measured Higgs boson rate and its SM expectation. The meaning of μ can vary depending on the assumptions made in each analysis; it can be defined for specific production and decay modes:

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \mu^f = \frac{BR^f}{(BR^f)_{SM}} \quad (1.24)$$

where σ_i is the cross section for each production mode ($i = ggF, VBF, WH, ZH, t\bar{t}H$) and BR^f is the branching ratio (BR) per final state ($f = ZZ, WW, \gamma\gamma, \tau\tau, b\bar{b}$).

Since σ_i and BR^f cannot be separately measured without additional assumptions, only the product of μ_i and μ^f can be extracted experimentally. An example of such additional assumption is that μ are the same for all

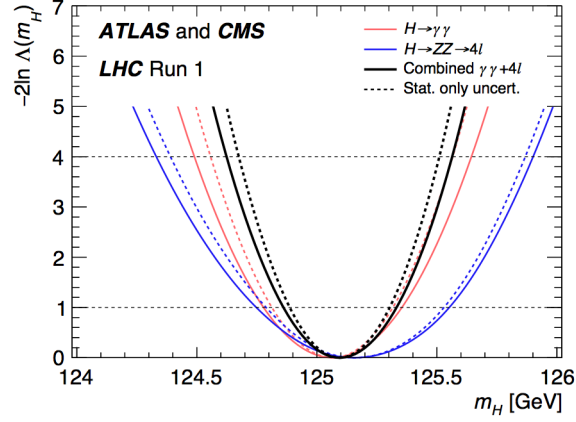


Figure 1.20: Scans of twice the negative log-likelihood ratio $-2\ln\Lambda(m_H)$ as functions of the Higgs boson mass m_H for the ATLAS and CMS combination of the $H \rightarrow \gamma\gamma$ (red), $H \rightarrow ZZ^* \rightarrow 4\ell$ (blue), and combined (black) channels. The dashed curves show the results accounting for statistical uncertainties only, with all nuisance parameters associated with systematic uncertainties fixed to their best-fit values. The intersection of the $-2\ln\Lambda(m_H)$ at 1 and 4 respectively represent the 1 and 2 standard deviation intervals.

production modes involving interaction with bosons (entering in the VBF and VH production modes) and with fermions (entering in the ggH and $t\bar{t}H$ production mechanisms).

Figure 1.21 and 1.22 show respectively the results for the signal strength per production mode and decay channel, and the two dimensional plot of the signal strength for bosonic versus fermionic production modes.

κ -framework

The κ -framework is a formalism that has been widely used in the ATLAS and CMS Higgs boson property studies and consists in computing the $\sigma \cdot BR$ quantities by scaling the couplings of the Higgs boson to other SM particles with free parameters κ , where κ is the ratio of the coupling to the Higgs boson with respect to the SM ($\kappa = g/g_{SM}$).

Relying on the assumptions of the Higgs being a $\mathcal{CP}$ -even scalar particle and under the narrow-width approximation, the production and decay rates of the Higgs boson can be factorized, such that the $\sigma \times BR$ can be parameterized as:

$$\sigma_i \times BR^f = \frac{\sigma_i(\vec{\kappa}) \times \Gamma^f(\vec{\kappa})}{\Gamma_H} \quad (1.25)$$

where Γ_H is the total width of the Higgs boson and Γ^f is the partial width of the Higgs boson decay to the final state f.

Coupling modifiers (κ) are introduced to parameterize potential deviations

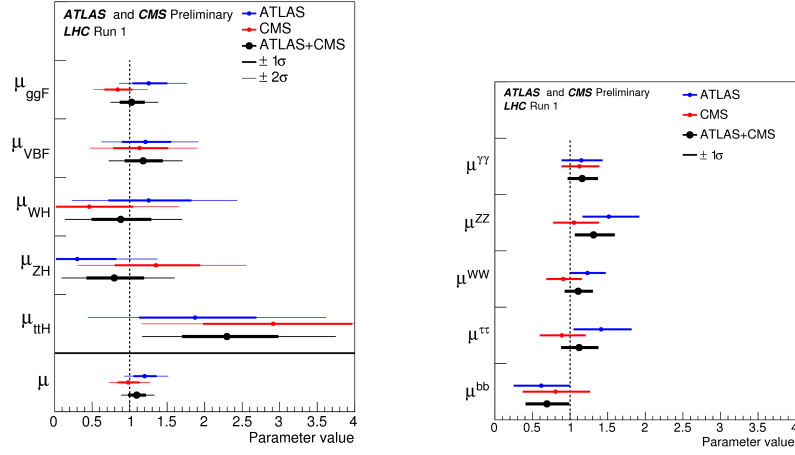


Figure 1.21: Results for the production (left) and decay (right) signal strengths from the combination of ATLAS and CMS [29]. The results for each experiment are superimposed. The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals.

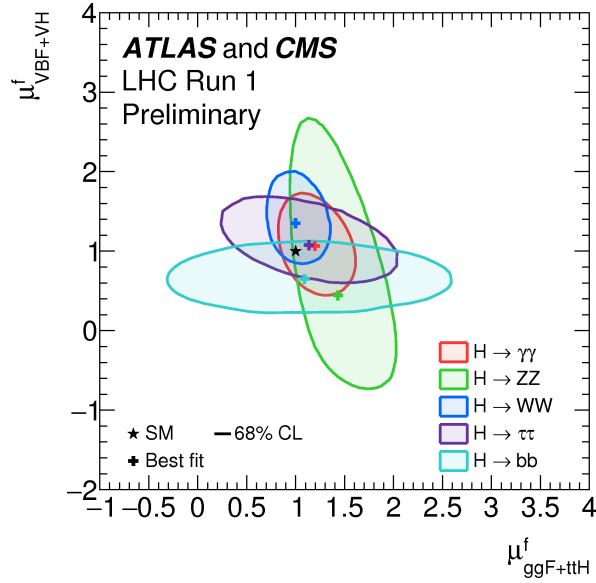


Figure 1.22: Likelihood contours in the $(\mu_{ggH, \bar{t}tH}, \mu_{VBF, VH})$ plane for the combination of ATLAS and CMS, shown for the five decay channels: $H \rightarrow ZZ, WW, \gamma\gamma, \tau\tau, bb$. The results are shown as 68% CL contours, together with the most probable values of the data and the SM expectation.

from the SM predictions of the Higgs boson couplings to SM bosons and fermions and are defined as follows for a given production or decay mode

(referred to as j):

$$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}} \quad \kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}} \quad (1.26)$$

A global fit with κ parameters free for all SM particles has limited sensitivity for some of them, like κ_t and κ_b . Scenarios with more restrictive constraints dedicated to specific classes of BSM theories have also been considered, like common scale factors for all fermions and bosons defined as κ_F and κ_V . Results for the combination of ATLAS and CMS and for the individual decay channels are shown in Figure 1.23; no deviations have been observed with respect to the SM expectations.

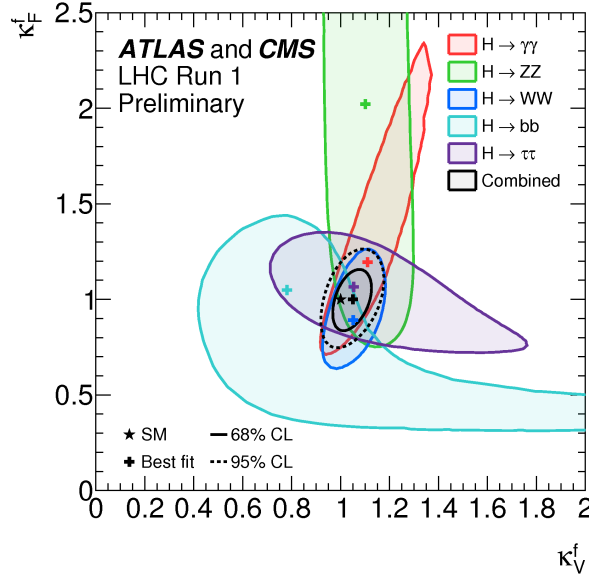


Figure 1.23: Confidence regions in the (κ_F, κ_V) plane for the combination of ATLAS and CMS and for the individual decay channels, assuming that all coupling modifiers are positive [29].

1.3.3.3 Fiducial and differential cross section measurements

Fiducial Cross Sections

Fiducial cross sections are measured to minimize the model dependence of the extrapolation to phase-space regions not covered by the detector acceptance and are corrected for detector effects (efficiencies, resolution) to be directly compared to theoretical calculations. Fiducial volumes are defined by the acceptance of the detector and the selection efficiency, therefore it is different between the two experiments.

In the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel, the extraction of the signal yield for the measurement of the fiducial cross section is performed through a fit to the $m_{4\ell}$ distribution using shape templates for the signal and background

contributions.

The inclusive fiducial cross section measured by ATLAS [30] and CMS [31] compared to their theoretical expectations are reported below:

$$\sigma_{fid,ATLAS} = 2.11_{-0.47}^{+0.53}(\text{stat.}) \pm 0.08(\text{syst.}) \text{ fb} \quad \sigma_{fid,ATLAS}^{SM} = 1.30 \pm 0.13 \text{ fb} \quad (1.27)$$

$$\sigma_{fid,CMS} = 1.11_{-0.35}^{+0.41}(\text{stat.})_{-0.10}^{+0.14}(\text{syst.})_{-0.02}^{+0.08}(\text{model}) \text{ fb} \quad \sigma_{fid,CMS}^{SM} = 1.15_{-0.13}^{+0.12}(\text{stat.}) \text{ fb} \quad (1.28)$$

The results of all measurements are compared with theoretical calculations based on NNLO QCD results and no significant deviations are observed.

Differential Cross Section

The differential measurements are performed in several observables related to the Higgs boson production and decay modes, chosen to be sensitive to its production mechanisms as well as spin/ $\mathcal{CP}$ quantum numbers, and among all, to test perturbative QCD predictions, probe the parton distribution functions of the proton and the relative rates of Higgs boson production modes.

The measured differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ $H \rightarrow \gamma\gamma$ [32, 33] and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ [34, 35] have been compared to selected theoretical calculations of the Standard Model expectations.

In the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel, ATLAS has performed the differential XS measurements subtracting the backgrounds within a mass window around the Higgs mass in each bin (namely m_H in [118., 129.] GeV) while CMS has performed it fitting the $m_{4\ell}$ shape distribution. Figure 1.24 shows the transverse momentum distribution on the Higgs boson in the $ZZ \rightarrow 4\ell$ decay channel for both experiments. No significant deviations are observed with respect to the theoretical predictions (normalized to the most precise value measured by the LHC XS WG). In the $H \rightarrow \gamma\gamma$ channel both the experiments have performed the measurements fitting the $m_{\gamma\gamma}$ distribution and the results show no significant deviations with respect to the theoretical predictions within the uncertainties (Figure 1.25). The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ measurements of differential cross sections are performed fitting the transverse mass defined as:

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss}|^2} \quad (1.29)$$

and subtracting the background contribution.

Figure 1.26 shows the results for the transverse momentum of the Higgs, no significant deviations have been observed.

1.3.3.4 Spin measurements

The spin/ $\mathcal{CP}$ of the Higgs boson in the SM is predicted to be $J^{\mathcal{CP}} = 0^{++}$, but Beyond SM (BSM) theories could predict the boson with other states

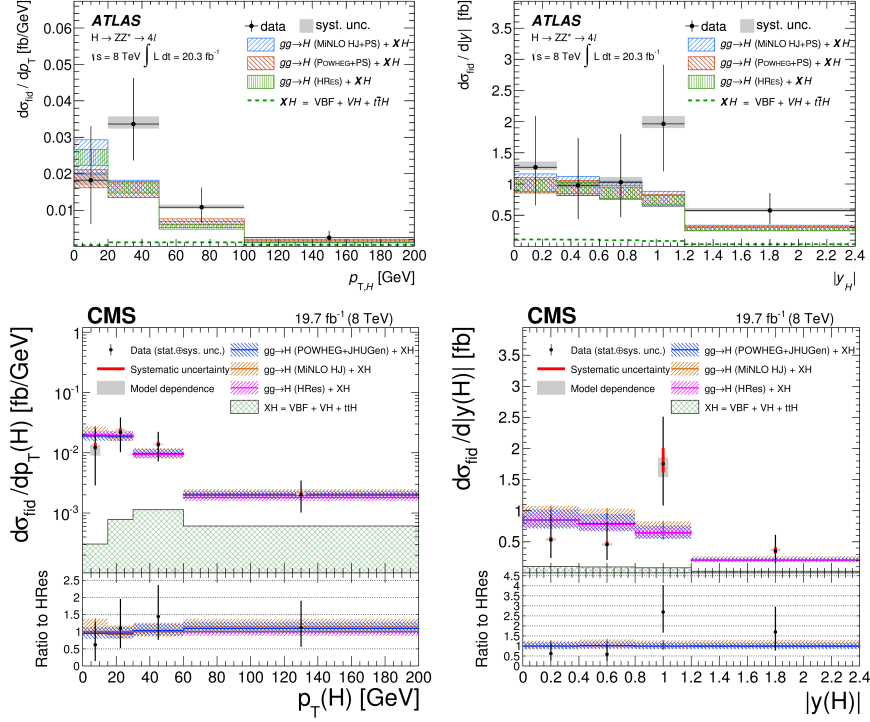


Figure 1.24: Results of the differential fiducial cross section measurements and comparison to the theoretical estimates for two kinematic variables: the Higgs boson transverse momentum and the pseudo-rapidity in ATLAS (up) and CMS (down). Theoretical estimates are superimposed: the dominant ggH contribution is modelled by several MC generators as shown in the legends.

of spin or $\mathcal{CP}$, or even a mixture of $\mathcal{CP}$ -even and $\mathcal{CP}$ -odd states.

Measurements of the Higgs spin-parity and tensor structure are based on the angular analysis of decays to vector boson pairs. The presence of anomalous non-scalar components would indicate a mixed state and new physics.

Tests on several alternative hypothesis of spin-parity have been carried out to assert the Higgs boson as a $\mathcal{CP}$ -even scalar particle.

Based on the full Run 1 dataset, the studies are only plausible with bosonic channels due to their good enough sensitivities to the presence of the Higgs boson. In the ATLAS experiment, the hypotheses are based on the Effective Field Theory (EFT) approach [36], which assumes a general effective Lagrangian compatible with Lorentz invariance. In contrast, in the CMS experiment, the spin/ $\mathcal{CP}$ models are based on an anomalous coupling approach [37], which assumes the general amplitude compatible with the Lorentz and gauge invariance.

The discriminants used in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel include the

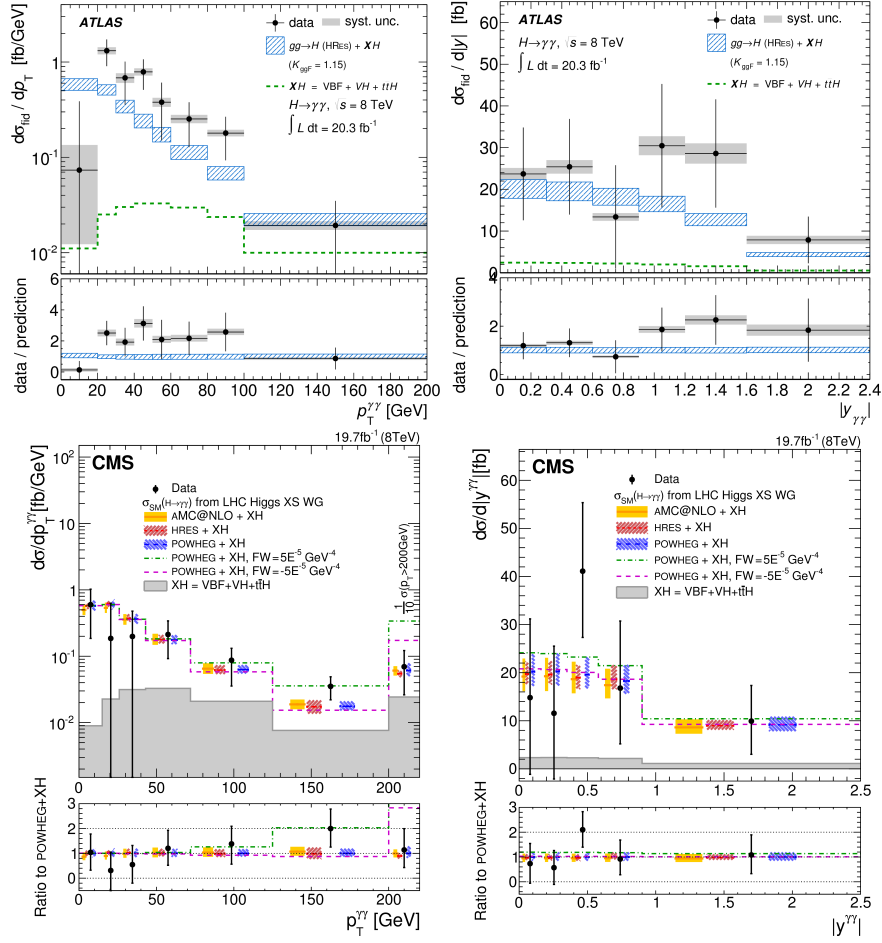


Figure 1.25: Results of the differential fiducial cross section measurements and comparison to the theoretical estimates for two kinematic variables: the transverse momentum and the pseudo-rapidity of the di-photon system in ATLAS (up) and CMS. Theoretical estimates are superimposed, in which the acceptance of the dominant ggH contribution is modelled by several MC generators as shown in the legends.

production and decay angles of the final states leptons, the invariant masses of the two di-lepton systems as well as the invariant mass of four leptons system. In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel, kinematic variables of the di-lepton system, such as $\Delta\phi_{ll}$, p_{ll}^T and m_{ll} , are sensitive to the spin/ $\mathcal{CP}$ studies. In the $H \rightarrow \gamma\gamma$ channel, spin-1 is forbidden by the Landau-Yang theorem, thus only spin-2 hypotheses are tested in this channel.

The test statistic ($\tilde{q}$) is used in order to compare the goodness of the fit of two models (as shown in Figure 1.27) and it is defined as the ratio of the profiled Likelihood under two hypothesis, namely for the data under the SM

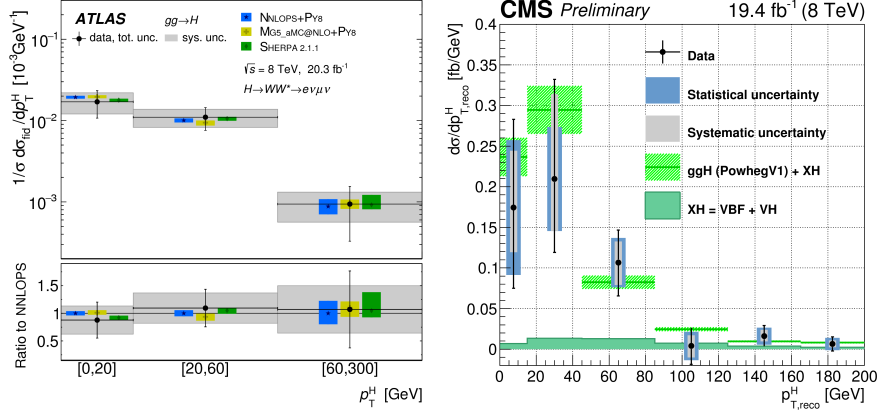


Figure 1.26: Results of the differential fiducial cross section measurements and comparison to the theoretical estimates for the transverse momentum of the Higgs in ATLAS (up) and CMS (down). CMS shows the ggH contribution superimposed to the other different production modes while ATLAS only gives measurement of the ggH dominant contribution.

hypothesis over alternative hypothesis in this particular case.

A combined study for spin/ $\mathcal{CP}$ measurement in the three bosonic channels has been performed [38, 39] and results show that data strongly favors the SM hypothesis ($J_{SM}^P = 0^+$), which is a $\mathcal{CP}$ -even scalar boson, while all the tested alternative hypotheses other than the SM hypothesis (J_{alt}^P) are excluded at more than 99.9% confidence level, as shown in Figure 1.27.

1.3.3.5 Constraints on the Higgs boson width

In the Standard Model, the width of the Higgs boson at $m_H = 125 \text{ GeV}$ is extremely small (4.1 MeV [4]). Unfortunately, since from direct measurements the invariant mass of the Higgs decay products ($m_{\gamma\gamma}$ and $m_{4\ell}$) can be reconstructed with poor resolution, the LHC is only sensitive to the Higgs width if it is in a few GeV range.

The SM Higgs boson is a narrow resonance, as such it is mainly produced on-shell; the off-shell production fraction being $\sim 10\%$ of the total. This feature leads to a relation between production rates, Higgs couplings and the width.

Constraints on the Higgs boson width can therefore be obtained by the off-shell Higgs boson event yields (normalized to the Standard Model prediction) in the $ZZ \rightarrow 4\ell$, $ZZ \rightarrow 2\ell 2\nu$ and $WW \rightarrow e\nu\mu\nu$ final states.

The cross-section $\sigma_{off-shell}^{gg \rightarrow H^* \rightarrow VV}$ for the off-shell Higgs boson production through gluon fusion with subsequent decay into vector-boson pairs is proportional to the product of the Higgs boson couplings to gluon and vector bosons squared for production and decay and, unlike the on-shell Higgs boson production,

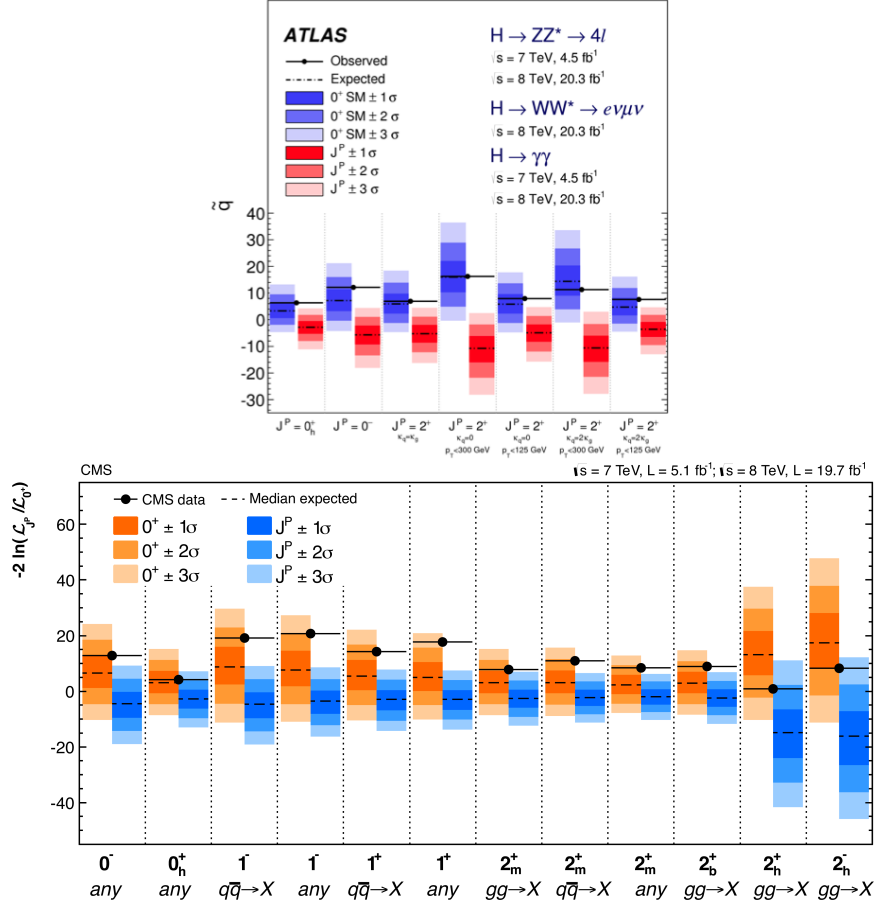


Figure 1.27: Summary of the expected and observed values for the test-statistic ($\tilde{q}$) distributions for the alternative hypothesis tested with respect to the SM Higgs boson in ATLAS (left) and CMS (right). The bands represents the 1, 2, and 3 σ around the median expected value for the SM Higgs boson and alternative hypothesis. The black point represents the observed value.

it is independent of the total Higgs boson decay width Γ_H :

$$\mu_{off-shell}(\hat{s}) = \frac{\sigma_{off-shell}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})}{\sigma_{off-shell,SM}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})} = \kappa_{g,off-shell}^2(\hat{s}) \cdot \kappa_{V,off-shell}^2(\hat{s}) \quad (1.30)$$

$$\mu_{on-shell}(\hat{s}) = \frac{\sigma_{on-shell}^{gg \rightarrow H \rightarrow VV}(\hat{s})}{\sigma_{on-shell,SM}^{gg \rightarrow H \rightarrow VV}(\hat{s})} = \frac{\kappa_{g,on-shell}^2(\hat{s}) \cdot \kappa_{V,on-shell}^2(\hat{s})}{\Gamma_H/\Gamma_H^{SM}} \quad (1.31)$$

Assuming identical on-shell and off-shell Higgs boson coupling scale factors, the ratio of the off-shell and on-shell Higgs boson couplings leads therefore

to the following relation:

$$\frac{\mu^{off-shell}}{\mu^{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}} \quad (1.32)$$

The NNLO k-factor for the $gg \rightarrow VV$ process is not precisely known from theory and the two experiments have choose two different approaches: CMS assumes the same NNLO k-factor as for the signal and, in doing this, adds a 10% uncertainty on the measurement, while ATLAS provides the result as a function of the ratio of these two ($R_{H^*}^B = \frac{k(gg \rightarrow ZZ)}{k(gg \rightarrow H^* \rightarrow ZZ)}$). Observed upper limit on the Higgs boson width have been set [40, 41] with a confidence level (CL) of 95%, namely:

$$\frac{\Gamma_H}{\Gamma_H^{SM}} < 4.8 - 7.7(7.0 - 12) \quad \text{given for } 0.5 < R_{H^*}^B < 2.0 \quad (\text{ATLAS}) \quad (1.33)$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} < 3.2(6.5) \quad (\text{CMS}) \quad (1.34)$$

where numbers in parenthesis are the corresponding expected upper limit and $R_{H^*}^B$ is the ratio of the gg-induced background over the signal in the off-peak region. The range 0.5 – 2 is chosen for the variation of the k-factor ratio $R_{H^*}^B$ in order to include the full correction from the signal k-factor $k(gg \rightarrow H^* \rightarrow ZZ)$ in the variation range.

1.3.4 Summary

The Run1 LHC data taking has been characterized by the Higgs boson discovery with a mass of $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV with evidence in the gluon fusion and vector boson fusion production modes.

After the Higgs boson discovery, measurements of its properties have been performed to assure the consistency of the couplings of the Higgs with the SM expectations.

Among this results the combined signal strength has been found to be perfectly consistent with the SM predictions:

$$\mu = 1.09 \pm 0.07(\text{stat.}) \pm 0.04(\text{exp.syst.}) \pm 0.03(\text{th.bkg.})_{-0.06}^{+0.07}(\text{th.sig}) \quad (1.35)$$

Test on the signal strength per production and decay mode and on couplings to SM particles, have shown consistency with the SM predictions too.

First measurements of the inclusive and differential cross sections in the most sensitive decay channels have been performed: no significant deviations from SM have been observed with the allowed statistical sensitivity.

Tests for different spin-parity hypothesis have excluded non SM J^P hypothesis with $CLs > 99.9\%$ and indirect limits on the Higgs boson width quote results better than $\Gamma_H < 5 \times \Gamma_H^{SM}$ at 95% CL.

The increasing statistics will allow for precise measurement of the Higgs boson properties in the near future.

Chapter 2

The ATLAS experiment at the LHC



Figure 2.1: The ATLAS Collaboration at building 40, CERN

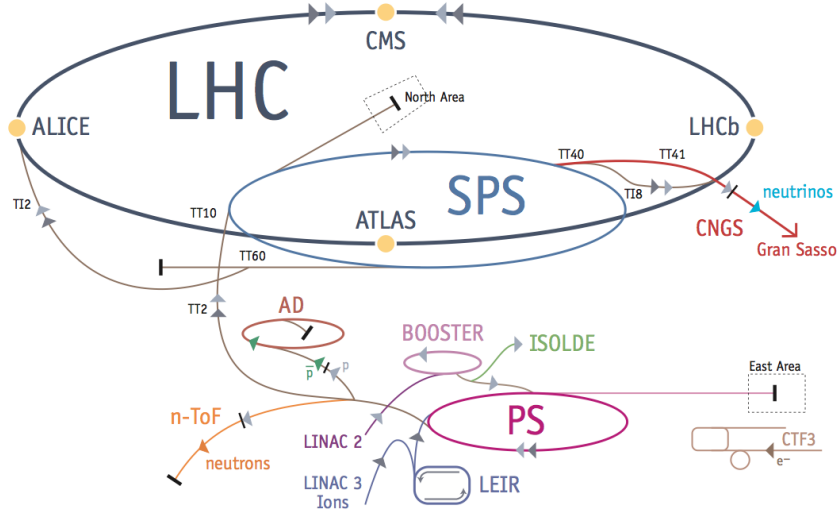


Figure 2.2: Schematic view of the Large Hadron Collider and the CERN accelerator complex.

2.1 Introduction

ATLAS is a particle physics experiment at the Large Hadron Collider at CERN that is searching for new discoveries in the head-on collisions of protons of extraordinarily high energy.

The Large Hadron Collider (LHC) is currently the world's largest hadron collider, with protons accelerated in a 27 km circumference synchrotron and with a design collision energy of 14 TeV.

Two transfer tunnels connect the LHC to the CERN accelerator complex that is used as injector. The protons are pre-accelerated in several stages (Figure 2.2) in fact, firstly the LINAC2 linear accelerator brings the protons to an energy of 50 MeV and feeds the Proton Synchrotron Booster (PSB), where they are accelerated to 1.4 GeV. Then, the protons are injected into the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), where their energy is increased to 26 GeV and 450 GeV, respectively. Finally injected into the LHC, the protons get ramped up to their operating energy¹. For one month a year the LHC is operated in heavy ion mode colliding lead nuclei at $\sqrt{s} = 1045$ TeV or p-Pb at $\sqrt{s} = 8.16$ TeV.

The number of events per second generated in the LHC collisions for given physics process is related to the cross section of the process under study (σ) by the following relation:

$$N_{ev} = L\sigma \quad (2.1)$$

¹The operating energy was 3.5 TeV in 2011, 4 TeV in 2012, 6.5 TeV in 2015-2016.

where L is the machine luminosity and only depends on the beam parameters; i.e., for a Gaussian beam distribution, it can be written as:

$$L = \frac{N_b n_b f_{rev} \gamma_r}{4 \pi \epsilon_n \beta^*} F \quad (2.2)$$

where N_b is the number of particle per bunch, n_b is the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the interaction point, and F is the geometric luminosity reduction factor due to the crossing angle at the interaction point.

High beam energies and high beam intensities are the essential requirement for the exploration of rare events in the LHC collisions. The general LHC design parameters are reported in Table 2.1.

In order to bend the two proton beam trajectories 1232 dipoles are used. An LHC dipole has a length of 14.3 m and is made of superconducting magnets which operate at a temperature of 1.9 K . These dipoles provide a magnetic field of 0.535 T in the injection stage (beam energy 450 GeV) up to 8.33 T for the nominal 7 TeV energy per beam corresponding to an average magnetic field of 5.3 T along the 27 km . The beam acceleration and energy loss compensation is done using eight RF cavities that produce a field of 5.5 MV/m .

The experiments that operate along the LHC ring are:

- ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) that are two general purpose experiment covering the wide range of physics that can be studied at LHC. The main goal for these two experiments is to discover and measure the properties of the Higgs boson, and to probe the physics beyond the Standard Model, like evidence for extra dimension models or the discovery of new heavy particles predicted for instance in supersymmetric theories.
- LHCb (Large Hadron Collider beauty experiment) uses a lower luminosity at the interaction point ($L = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$) and studies the $\mathcal{CP}$ -symmetry violation in the heavy b -quark system.
- ALICE (A Large Ion Collier Experiment) is the LHC experiment dedicated to the heavy ion physics and it is designed to study the phase transition to the quark-gluon plasma. For this kind of studies, LHC provides Pb-Pb ion collisions and p-Pb collisions in addition to p-p.
- TOTEM (TOTal Elastic and diffractive cross-section Measurement) is placed near the CMS experiment interaction point and measures the total proton proton cross-section, elastic scattering, and diffractive processes.

- LHCf (Large Hadron Collider forward experiment) is located close to the ATLAS experiment interaction point and will measure the forward particles created during the LHC collisions in order to provide a better understanding of high-energy cosmic rays.

Table 2.1: General LHC design parameters.

LHC General parameters	
Energy at collision	7 TeV
Energy at injection	450 GeV
Dipole field at 7 TeV	8.33 T
Coil inner diameter	56 mm
Luminosity	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
DC beam current	0.56 A
Bunch spacing	7.48 m
Bunch separation	24.95 ns
Number of particles per bunch	1.1×10^{11}
Normalized transverse emittance (r.m.s.)	3.75 μm
Total crossing angle	300 μrad
Luminosity lifetime	10 h
Energy loss per turn	7 KeV
Critical photon energy	44.1 eV
Total radiated power per beam	3.8 kW
Stored energy per beam	350 MJ
Filling time per ring	4.3 min

This Chapter presents an overview of the ATLAS detector, with particular attention on the sub-detectors used to measure the energy and momentum of the leptons.

2.2 The ATLAS Detector

The ATLAS experiment [3] has been designed to be a multi-purpose particle physics detector in order to be versatile enough to detect physics signals with a wide range of signatures and it has approximately a forward-backward symmetric cylindrical geometry. The ATLAS detector (Figure 2.3) is over 25 meters high, and almost 44 meters long. It weighs approximately 7000 tons and it has been built around the LHC beam pipe, about 100 meters underground.

The detector is centered on one of the LHC collision points and the particles produced in the collisions emerge from the center of the detector in all directions.

The design of the ATLAS experiment has been thought and realized in order

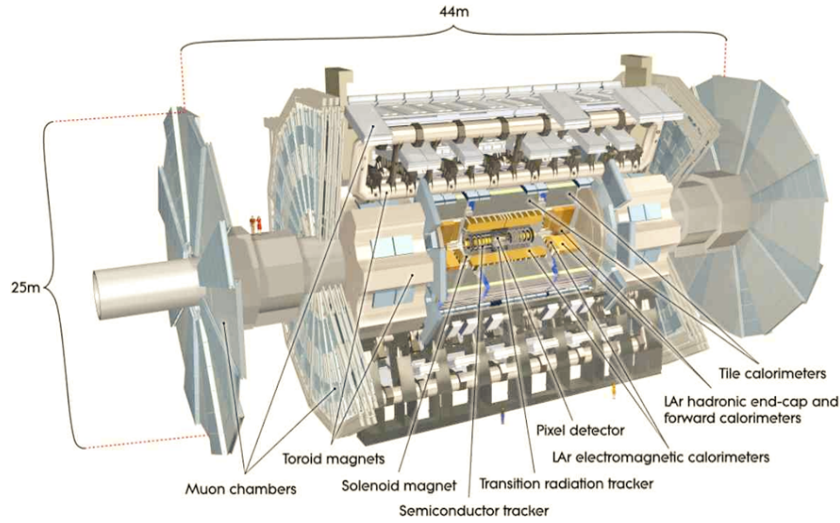


Figure 2.3: Schematic view of the ATLAS apparatus; the beam pipe runs through the middle of the detector from the left to the right of the figure.

to explore the high physics potential of the LHC proton-proton interactions and to record the paths and energies of the particles emerging from the collisions.

The main physics goals that ATLAS is aiming for are:

- A precise measurement of Standard Model parameters, with particular focus on the top quark properties. Measurement of production cross section of W and Z vector bosons at the new energy regime, precise measurement of the masses and the couplings and spin of the top quark could be achieved due to the very high production rates of the electroweak bosons as well as of the top quark. Moreover, a study of the $\mathcal{CP}$ violation using the B mesons decay could also be carried out.
- Exploration of the origin of the electroweak symmetry breaking mechanism: ATLAS has been able to discover a resonance which has been confirmed to be the Standard Model Higgs boson associated to the Higgs mechanism. The next goal is therefore to explore the Higgs sector and measure its properties.
- The search for physics beyond the Standard Model: the supersymmetric extensions of the Standard Model are of high interest because they give a possible dark matter candidate, the lightest supersymmetric particle. ATLAS is also searching for the existence of Extra Dimensions and the presence of new neutral (Z') and charged (W') vector bosons foreseen by the unification models that use extended gauge group (i.e. extra $U(1)$ in Kaluza-Klein Model). On this purpose, AT-

LAS has also put limits on the existence of New Physics beyond the SM.

Many of the processes mentioned have a small cross sections, therefore high luminosity is required for the LHC. However, due to the inelastic proton-proton cross section being of the order of $\sigma \sim 60(78) \text{ mb}$ at $\sqrt{s} = 7(13) \text{ TeV}$, every interesting candidate event will be accompanied, on average, by 23 inelastic collisions at the design luminosity (Figure 2.4).

The search for the SM Higgs boson has been used as a benchmark for the design of the ATLAS detector.

Since the dominant decay channel of the Higgs boson was unknown, due to its unknown mass, the detector was designed to cope all the possible decay scenarios. These requirements, combined with the high luminosity, high beam energy and high background production at LHC have been translated into the following set of design requirements:

- Due to the very high luminosity and large particle flux, the detectors need fast, radiation-hard electronics and sensor elements. In addition, high granularity is needed to handle the large number of particles and to reduce the influence of overlapping events.
- Large acceptance in pseudo-rapidity with almost full azimuthal angle coverage is required. This ensure that no high transverse momentum particles can escape detection.
- Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker are essential. For off-line tagging of τ -leptons and b -jets, vertex detectors close to the interaction region are required to resolve secondary vertices.
- Excellent electromagnetic (EM) calorimetry is needed for electron and photon identification and measurements as well as a full coverage hadronic calorimetry for accurate jet and missing transverse energy measurements.
- Good muon identification and momentum resolution over a wide range of momenta and the ability to determine unambiguously the charge of high- p_T muons are fundamental requirements.
- Highly efficient triggering on objects with sufficient background rejection is a prerequisite to achieve an acceptable trigger rate for most of the physics processes of interest.

2.3 ATLAS Geometry

The ATLAS experiment uses a right-handed coordinate system: the origin is centered to the nominal position of the interaction point, the beam defines

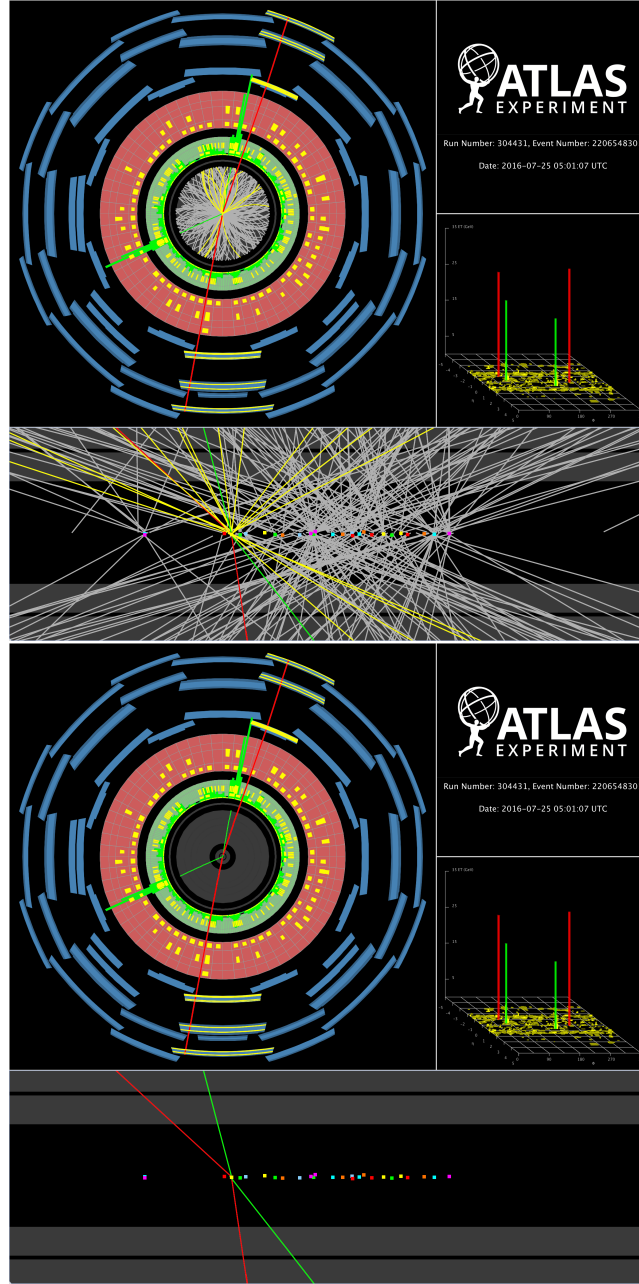


Figure 2.4: A display of a candidate Higgs boson event reconstructed in the $2\mu 2e$ final state from $p-p$ collisions recorded by ATLAS at 13 TeV. The Higgs boson candidate is reconstructed in a beam crossing with 25 additionally reconstructed primary vertices from the minimum bias interactions. In the left display, the red lines show the path of the two muons including the hits in the muon spectrometer, the green lines show the paths of the two electrons together with the energy deposit in the electromagnetic calorimeter, and the yellow tracks are the remaining charged particles from the Higgs boson candidate vertex. No jet has been reconstructed with $p_T > 30$ GeV. The grey tracks correspond to the charged particles from the 25 pileup vertices with $p_T > 0.5(8)$ GeV in the up (down) plot and the colored squares in the lower display correspond to the position of the reconstructed vertices.

the z -axis direction that have the same orientation of the counter-clock wise rotating beam while the $x-y$ plane is transverse to the beam direction. The x -axis points from the interaction point towards the center of the LHC ring and the y -axis is defined as pointing vertically upwards.

A cylindrical coordinate system is used, defined by R , ϕ and θ .

- R is the radial vector from the interaction point and out ($R = \sqrt{x^2 + y^2}$);
- ϕ is the azimuthal angle, it is measured from positive x -axis in the clockwise direction when looking at the positive z direction ($-\pi < \phi < \pi$);
- θ is the polar angle, formed by the direction of the emitted particle with the positive z -axis: it is measured from the beam axis ($0 < \theta < \pi$).

At collider experiments it is quite common to introduce the pseudo-rapidity variable, η , defined as:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) \quad (2.3)$$

Figure 2.5 shows an illustration of the values of pseudo-rapidity according to different directions from the coordinate system's origin.

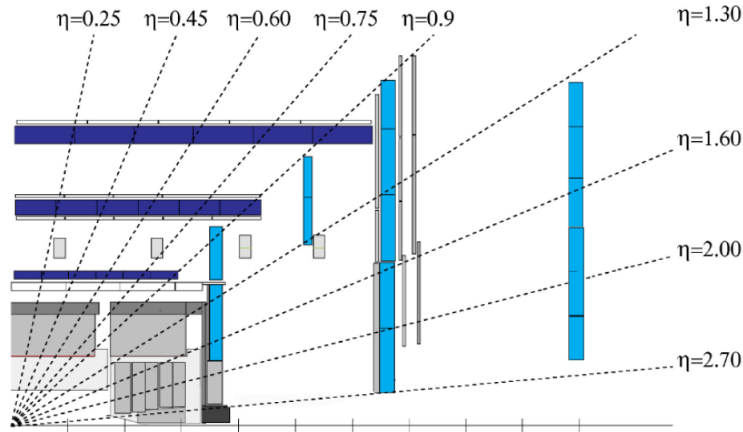


Figure 2.5: An illustration of the values of the pseudo-rapidity η according to different directions from the coordinate system's origin (lower left corner). The polar angle θ would be measured from the horizontal axis, positive upwards. The dark and light blue boxes are the muon spectrometer's barrel and end-cap modules, respectively.

In the case of massive objects such as jets, the rapidity is used instead, as the pseudo-rapidity (η) can approximate the rapidity (y) only when the mass is negligible with respect to the energy.

$$y = \frac{1}{2} \ln\left(\frac{E + p_Z}{E - p_Z}\right) \quad (2.4)$$

This quantity transforms in additive way under Lorentz transformation, then the difference $\Delta y = y_2 - y_1$ is a relativistic invariant.

The transverse momentum p_T of a particle corresponds to the momentum component orthogonal to the beam axis ($p_T = p \sin\theta$); transverse momentum, transverse energy E_T , and missing transverse energy ($E_{T,miss}$) are defined in the x-y plane unless stated otherwise.

To fully describe the track of a particle additional parameters are used: d_0 and z_0 . The transverse impact parameter, d_0 (Figure 2.6), is the distance of the track's point of the closest approach to the beam axis in the transverse plane, while z_0 is the longitudinal distance of this particular point. The

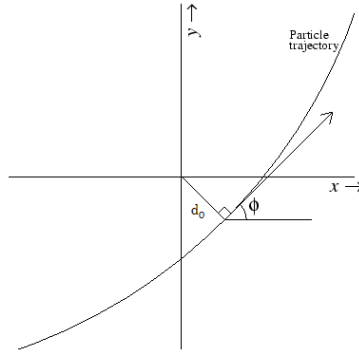


Figure 2.6: Schematic view of the transverse impact parameter d_0 associated to the particle trajectory; the primary vertex coincides with the origin of the axis.

spacial separation of two particle tracks or clusters of jets is expressed in terms of ΔR , defined as:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (2.5)$$

In the following sections the different subsystems of the ATLAS detector will be described giving particular attention to those used for the lepton identification and reconstruction.

2.4 The ATLAS sub-detectors

ATLAS is composed of a series of concentric sub-systems, each sensitive to different types of particles produced in the collisions and covers almost the whole solid angle with its onion structure.

The ATLAS detector is divided in three longitudinal regions: one is central (*barrel*), the other two lateral (*end-caps*)².

²Sub-detectors in the central part are named with the *barrel* prefix, the others with the *end-cap* prefixes

Starting from the interaction point the ATLAS detector consists of the inner detector, the magnet solenoid, the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer immersed in the toroidal air-core magnetic system.

The Inner Detector (ID) is aimed to track charged particles in order to reconstruct those coming from the same interaction vertex; it is composed of the Pixel Detector, the silicon microstrip detector (Semiconductor Tracker, SCT), and the straw tube Transition Radiation Tracker (TRT), each of which is indicated in Figure 2.7. The ID is surrounded by a thin superconducting solenoid which provides the 2T axial magnetic field, and by high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter that is able to measure the energy and the position of electromagnetic showers with $|\eta| < 3.2$.

The electromagnetic calorimeter is divided into a central barrel ($|\eta| < 1.475$) and end-cap regions on either end of the detector ($1.375 < |\eta| < 2.5$ for the outer wheel and $2.5 < |\eta| < 3.2$ for the inner wheel). In the region matched to the ID ($|\eta| < 2.5$), it is radially segmented into three layers. The first layer has a fine segmentation in η to facilitate e/γ separation from π_0 and to improve the resolution of the shower position and direction measurements. In the region $|\eta| < 1.8$, the electromagnetic calorimeter is preceded by a presampler detector to correct for upstream energy losses. An iron-scintillator/tile calorimeter gives hadronic coverage in the central rapidity range ($|\eta| < 1.7$), while a LAr hadronic end-cap calorimeter provides coverage over $1.5 < |\eta| < 3.2$. The forward regions ($3.2 < |\eta| < 4.9$) are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The calorimeters are designed to measure the energy of electrons, photons, and hadrons and they are sensitive to both charged and neutral particles. All particles except muons and neutrinos are stopped by the calorimeter system. The MS is therefore designed to measure the transverse momentum of muons leaving the calorimeter. The muon spectrometer (MS) surrounds the calorimetric system and consists of three large air-core superconducting magnets providing a toroidal field, each with eight coils, a system of precision tracking chambers, and fast detectors used to provide the trigger. The combination of all these systems provides charged particle measurements together with efficient and precise lepton and photon measurements in the pseudo-rapidity range $|\eta| < 2.5$.

Jets and $E_{T_{miss}}$ are reconstructed using energy deposits over the full coverage of the calorimeters, $|\eta| < 4.9$.

A three-level trigger system selects events to be recorded for off-line analysis.

The design resolution of each sub-detector part is given in Table 2.2.

Table 2.2: Target resolution and pseudorapidity measurement coverage region of the ATLAS detector for each component individually.

Detector component	Target resolution	Coverage
Inner Detector (ID)	$\frac{\sigma_{p_T}}{p_T} = 0.5\% \oplus 1\%$	$ \eta < 2.5$
Electromagnetic calorimeter (ECal)	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$	$ \eta < 3.2$
Hadronic calorimeter (HCal)		
Barrel and Hadronic End-Cap (HEC)	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$	$ \eta < 3.2$
Forward calorimeter (FCal)	$\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$	$3.1 < \eta < 4.9$
Muon Spectrometer (MS)	$\frac{\sigma_{p_T}}{p_T} = 10\% \quad p_T = 1 \text{ TeV}$	$ \eta < 2.7$

2.4.1 The Inner detector

The ATLAS Inner Detector (ID) (Figure 2.7) is the innermost sub-system of the ATLAS experiment; it is totally contained in the $2T$ central solenoid which bends charged particles in the x-y plane with an uniform coverage in ϕ and up to $|\eta| \leq 2.51$. It consists of central barrel layers, centered on the interaction point, and end-cap wheels or disks at either end of the barrel. It is made of three sub-detectors, built using the technologies of silicon sensors and straw drift tubes and it surrounds the LHC beam pipe that is fully contained in a 50 mm x 36 mm ultra-high vacuum vessel.

Figure 2.7 shows a cut-away of the ID barrel and end-caps.

The goals of this detector are to identify the primary interaction vertex and measure the impact parameter with high resolution; identify secondary vertices (for b-tagging) and measure the p_T of charged particles with a resolution up to 30% at $p_T = 500 \text{ GeV}$.

The high track density that is expected for the collision events in the LHC imposes a high granularity for this detectors; in fact, at the LHC design luminosity of $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, ~ 1000 particles will emerge from the interaction point every 25 ns. Moreover they have to work in a high-radiation environment.

In order to satisfy these requirements with the minimum amount of material (to limit the multiple scattering effect on the track momentum resolution), different technologies are used: pixel and silicon microstrips (Pixel and SCT) trackers together with the straw tubes of the transition radiation tracker (TRT).

The former two (the Pixel Detector and the Semi Conductor Tracker) are based on reverse-biased semiconductor technology, while the latter (the Transition Radiation Tracker) is a gaseous detector (Figure 2.8).

When charged particles cross the silicon sensors, they generate electron-hole

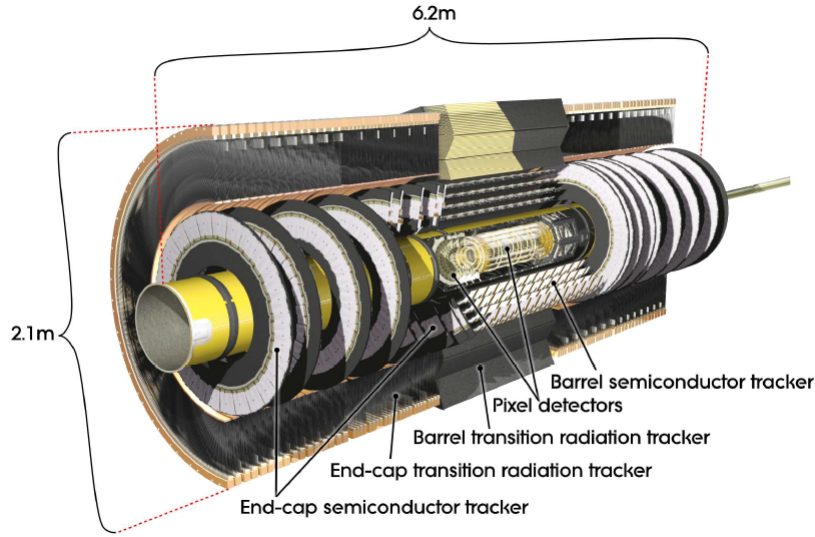


Figure 2.7: Scheme of the ATLAS Inner Detector.

pairs which can be collected with an applied electric field. This charge is recorded locally in the sensor, identifying the position of the particle. A similar process occurs in the straw drift tubes. Charged particles traversing the drift tubes ionize the gas contained within the tube. The electrons produced in this process are drifted, with an applied electron field, to the wire at the center of the straw, where they are recorded.

The use of different technologies is the result of a trade-off between high spatial resolution and a lightweight detector.

The density of the semiconductor substrate and the need for bulky cooling and readout services implies high interaction and radiation lengths causing multiple scattering and energy loss of the incoming particle, with a degradation of the quality of the momentum measurement. It was therefore decided to include in the Inner Detector a gaseous tracker. The gaseous tracker has a small number of radiation length, then it can measure a higher number of space points along the particle's tracks without multiple scattering and can exploit the transition radiation phenomenon to identify electrons and charged pions.

In order to maintain an adequate noise performance after radiation damage, the silicon sensors are kept at low temperature (between $-5^{\circ}C$ and $-10^{\circ}C$) with a cooling system that reaches the temperature of $-25^{\circ}C$ while the TRT operate at room temperature.

The Pixel detector is the closest sub-detector to the interaction point and provides the finest granularity. Comprised of over 80 million channels, the Pixel detector provides on average three measurements per charged particle and has a position resolution of $10\mu m$ in the $r - \phi$ plane and $115\mu m$ along

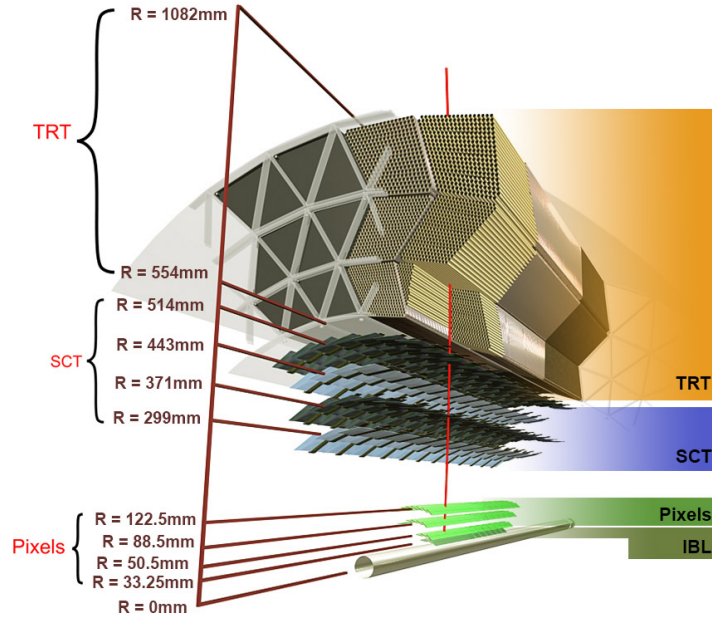


Figure 2.8: Detailed Layout of the Inner Detector (ID) including the new Insertable B-Layer (IBL).

z . The Pixel detector provides uniform coverage in ϕ and up-to $|\eta| < 2.5$. The SCT surrounds the Pixel detectors. Each SCT layer is composed of a double layer of silicon strips, whose axes are tilted with respect to one another. The pair of measurements at each SCT layer locates charged particles in $r - \phi$ with an accuracy of $17\mu m$ and with an accuracy of $580\mu m$ along z . The SCT provides between four and nine measurements per particle, with coverage up-to $|\eta| < 2.5$.

The TRT is the largest of the sub-detectors in the ID. The TRT is composed of ~ 300 thousand straw drift tubes that provide position measurements with an accuracy of $\sim 130\mu m$ in the $r - \phi$ plane in the barrel, and in the $z - \phi$ plane in the end-cap. A large number of hits, typically 36 per particle, is provided, with coverage up-to $|\eta| = 2.0$.

In addition to being a tracking detector, the TRT also provides particle identification through the detection of transition radiation since charged particles emit transition radiation (TR) photons when traversing the TRT. The probability of emitting a TR photon is a function of the Lorentz factor- γ : at a given momentum, electrons will emit more transition radiation photons than charged hadrons (i.e. pions).

During the first long shutdown, the ATLAS Detector has been upgraded for higher intensity running of the LHC. A new pixel layer, called the Insertable B-Layer (IBL), has been inserted at a radius of about 3.2 cm between the existing Pixel Detector and a new (smaller radius) beam-pipe. The IBL is

required to cope with the increased radiation level and pixel occupancy, as well as to improve the physics performance of the existing Pixel Detector of the ATLAS Experiment. As shown in Figure 2.9, this new pixel layer has improved the impact parameter resolution and has been able to compensate for degradation of the old Pixel Detector B-layer due to radiation damage, ageing and increasing data rates.

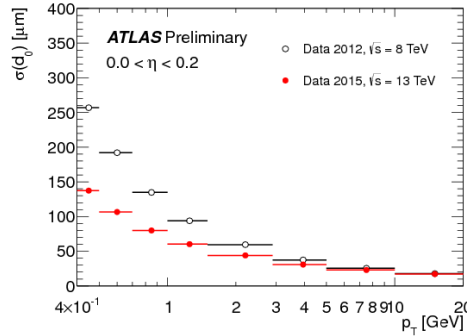


Figure 2.9: Resolution on the impact parameter before and after upgrading the Inner Detector (ID) with the Insertable B-Layer (IBL).

2.4.2 The Calorimeters

The ATLAS calorimeter system (Figure 2.10) measures the energy of electrons, photons and hadrons and it is composed by an electromagnetic calorimeter and an hadronic calorimeter, providing a pseudo-rapidity coverage up to $|\eta| < 4.9$ using different technologies.

The ATLAS calorimeters are “sampling” calorimeters: incident particles produce showers of energy in the calorimeter but only a fraction of the energy produced by the particle is measured by active detector sensors; the energy of the full shower can then be inferred from the observed energy.

2.4.2.1 The electromagnetic calorimeter

The Electromagnetic (EM) calorimeter is a lead-Liquid Argon (Pb-LAr) detector with lead absorber plates and Kapton electrodes. For this detector, both in the barrel and in the endcap region, an *accordion* geometry has been chosen for the absorbers and the electrodes (Figure 2.11) since it naturally ensures a good energy resolution and an almost full coverage along the azimuthal direction that is needed in order to have the maximum geometrical acceptance to reconstruct events with a very low cross section.

The EM calorimeter provides high granularity measurements, critical for particle identification in the range $|\eta| < 2.5$ and is segmented into three radial sections with different $\eta - \phi$ granularities. The first layer, referred to as

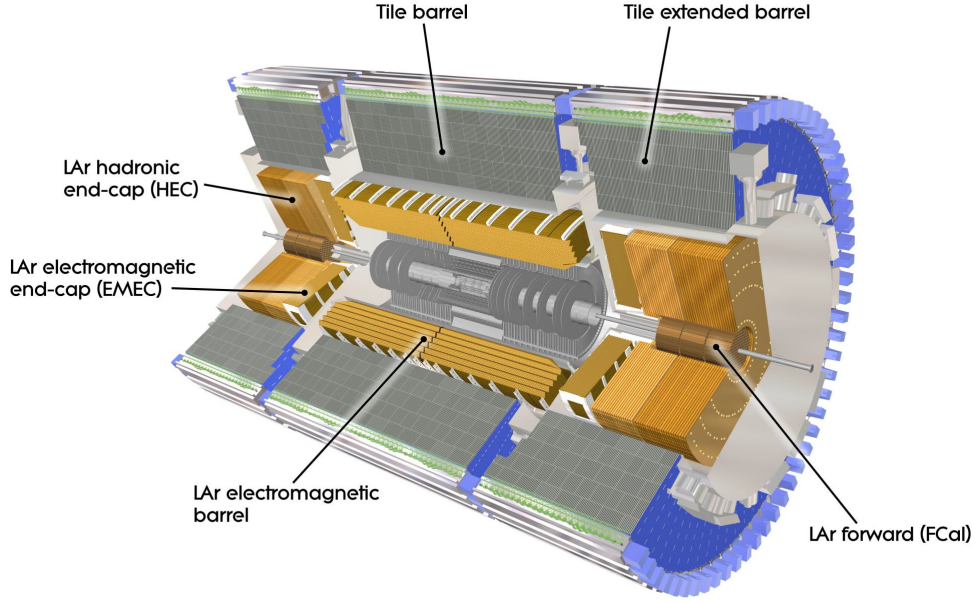


Figure 2.10: The ATLAS calorimetric system.

the “strips”, provides very fine segmentation in η ; the strips can separate between showers initiated by electrons or photons, and showers initiated by neutral pions. The second sampling provides most of the energy measurement and has fine segmentation in both η and ϕ . The third sampling is coarser, and adds additional depth to the calorimeter. The EM calorimeters cover the pseudorapidity range $|\eta| < 3.2$.

The EM calorimeter is composed by two identical half cylinders in the barrel region and by two coaxial wheels for each side in the endcap, covering respectively the pseudo-rapidity range of $1.4 \lesssim |\eta| \lesssim 2.5$ the innermost and $2.5 \lesssim |\eta| \lesssim 3.2$ the outer.

The thickness of the lead layers change as a function of η from 1.5 mm for $|\eta| \leq 0.8$ up to 2.2 mm for $0.8 \leq |\eta| \lesssim 3.2$; the radial thickness of the liquid argon volumes is 2.1 mm in the barrel and goes from 0.9 mm up to 3.1 mm in the endcaps. The total active thickness of a barrel module increases as a function of the radiation lengths (X_0), from $22 X_0$ to $30 X_0$ for $0 \leq |\eta| \leq 0.8$ and goes from $24 X_0$ to $33 X_0$ between $0.8 \leq |\eta| \leq 1.3$ while, in the endcap, goes from 24 to $38 X_0$.

The accordion fold amplitude of the Electromagnetic Endcap Calorimeter varies with the radius from the wheel center leading to a varying gap size. High-voltage requirements are therefore different in different radial regions and special care is needed in the characterization of the electrical properties

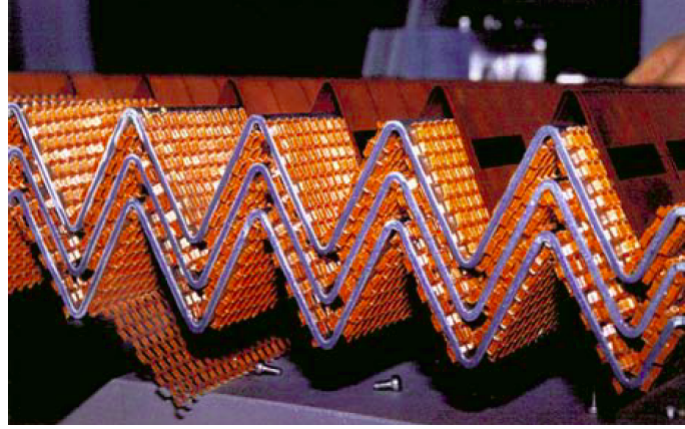


Figure 2.11: The accordion structure of Electromagnetic Barrel Calorimeter. Honeycomb spacers position the electrodes between the lead absorber plates.

of individual cells since these also vary with radius.

An excellent understanding of the electrical properties of each cell is crucial then for the calibration of the detector response.

The energy resolution of an electromagnetic calorimeter is given by the relation:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2} \quad (2.6)$$

where a is the stochastic term, b takes into account the electronic noise and c is the constant term that reflects local non-uniformities in the response of the calorimeter. For the ATLAS electromagnetic calorimeter, $a = 10\%$, $b = 0.5\%$ and $c = 0.7\%$. In the energy range 15 – 180 GeV, the reconstructed energy response is linear within $\pm 0.1\%$.

2.4.2.2 The hadronic calorimeter

The ATLAS hadronic sampling calorimeter covers a pseudo-rapidity range of $|\eta| \leq 4.9$ using different technologies, depending on the η value. In the region $|\eta| \leq 1.7$ a sampled calorimeter called Tile Calorimeter is installed, using steel layers with a thickness of 14 mm for the absorber and scintillator tiles for the active medium. In the endcaps ($1.5 \leq |\eta| \leq 3.2$) layers of copper are used as absorber due to higher radiation flux, alternated to volumes filled with LAr. In the Hadronic Endcap Calorimeter (HEC), Electrodes made of carbon-loaded kapton are positioned in the 8.5 mm gap between the copper plates forming a multi-gap electrode structure; each endcap cryostat contains two HEC wheels, each constructed from 32 azimuthal modules.

Finally, in the forward regions ($3.1 \leq |\eta| \leq 4.9$), the technology chosen is LAr volumes alternated to copper or tungsten layers.

Material and total thickness of the hadronic calorimeter has been chosen in

order to obtain a good hadronic calorimeter shower containment, to measure accurately the missing transverse energy ($E_{T,miss}$) and to reduce the punch-through in the muon spectrometer. The amount of material at $\eta = 0$ corresponds to 11 interaction lengths (λ).

The Hadronic Endcap Calorimeter (HEC) is a more conventional parallel-plate copper-LAr sampling calorimeter. Electrodes made of carbon-loaded kapton are positioned in the 8.5 mm gap between the copper plates forming a multi-gap electrode structure. Each endcap cryostat contains two HEC wheels, each constructed from 32 azimuthal modules.

The shaped signal is sampled every 25 ns, in time with the LHC clock and the samples are stored in an analog pipeline for readout after the Level-1 trigger processing; accepted events are digitized and read out.

The ATLAS hadronic calorimeter is characterized by two different energy resolution depending on the η region:

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\% \quad |\eta| \leq 3 \quad (2.7)$$

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E[\text{GeV}]}} \oplus 10\% \quad 3 \leq |\eta| \leq 5 \quad (2.8)$$

Figure 2.12 shows the resolution of the combined ECAL/HCAL calorimetry system at the $H6$ test beam.

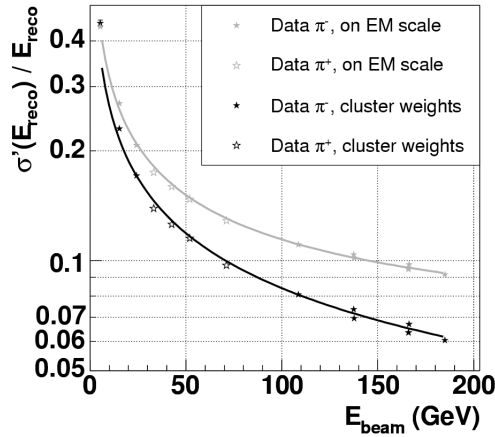


Figure 2.12: Resolution of the combined ECAL/HCAL calorimetry system; the weighted data (in black) exhibits a better resolution than the uncorrected data (in gray).

2.4.3 The Muon Spectrometer

The muon spectrometer is located in the outer part of the ATLAS detector and allow a very precise tracking of the high p_T muons with a good

transverse momentum resolution and provide the muon trigger for the experiment.

The MS operates in a toroidal magnetic field and its layout is shown in Figure 2.13. Over the range $|\eta| < 1.4$, magnetic bending is provided by the large barrel toroid, for $1.6 < |\eta| < 2.7$, muon tracks are bent by two smaller end-cap magnets inserted into both ends of the barrel toroid, and in the region $1.4 < |\eta| < 1.6$, the bending is provided by a combination of the barrel and end-cap fields.

Taking into account all the requirements in terms of performance, rate capability, granularity, ageing properties and radiation hardness, Monitored Drift Chambers (MDTs) and Cathode Strip Chambers (CSC) have been chosen for the precision measurement of the muon track while the Resistive Plate Chambers (RPC) and the Thin Gap Chambers (TGC) are used in order to provide the muon trigger to the experiment since they provide precise timing, well-defined p_T thresholds, and measure the muon coordinate in the direction orthogonal to that determined by the precision tracking chambers. The most important parameters that have been optimized in the design phase of this subsystem of the ATLAS experiment are:

- the resolution: a good p_T resolution of the order of few percent is needed for a reliable muon charge identification (especially for very high p_T muons) and a good reconstruction of final state decays in two muons (i.e. $Z \rightarrow \mu^+ \mu^-$) or four muons (i.e. $H \rightarrow ZZ^* \rightarrow 4\mu$). Moreover a uniform transverse momentum resolution is required in all the pseudo-rapidity range covered by the muon spectrometer.
- the second coordinate measurement: in order to obtain a better track reconstruction, it is necessary to detect the muons also in the non bending direction. A resolution better than 1 cm is required.
- the pseudo-rapidity coverage: a good pseudo-rapidity coverage up to $|\eta| \sim 3$ is needed to study all the physics processes that have muons in the final states.
- the bunch crossing identification: the time interval between two bunch crossing at the nominal luminosity is 25 ns and this automatically sets a limit on the time resolution for the trigger.

In Table 2.3 the main parameters of the ATLAS muon chambers are reported.

Muons in the MS, can be reconstructed in an independent way with respect to the inner detector from ~ 3 GeV (that approximatively correspond to the energy loss in the calorimeters) up to 3 TeV. To reconstruct the muon transverse momentum, they are bent (along the η view) by the toroidal magnetic field generated by the air-core toroid magnets.

Figures 2.13 and 2.14 shows two sections of the ATLAS muon system. In

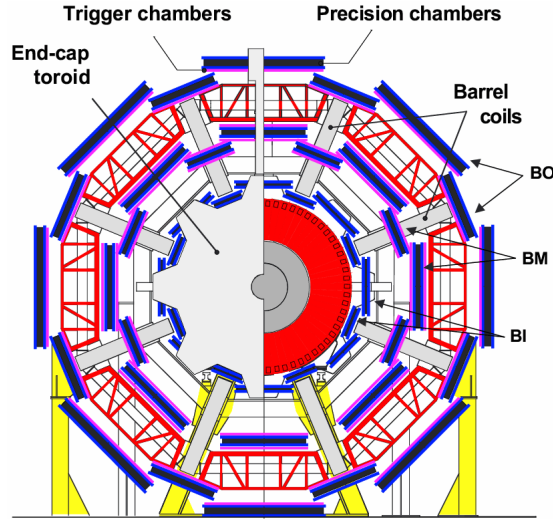


Figure 2.13: Radial section of the barrel of the ATLAS Muon Spectrometer. The MDT precision chamber are organised in projective towers of three layers (stations) each. The three stations are denominated *barrel inner* (BI) *barrel middle* (BM) and *barrel outer* (BO). A third letter is added to the denomination to identify large (L) or small (S) chambers.

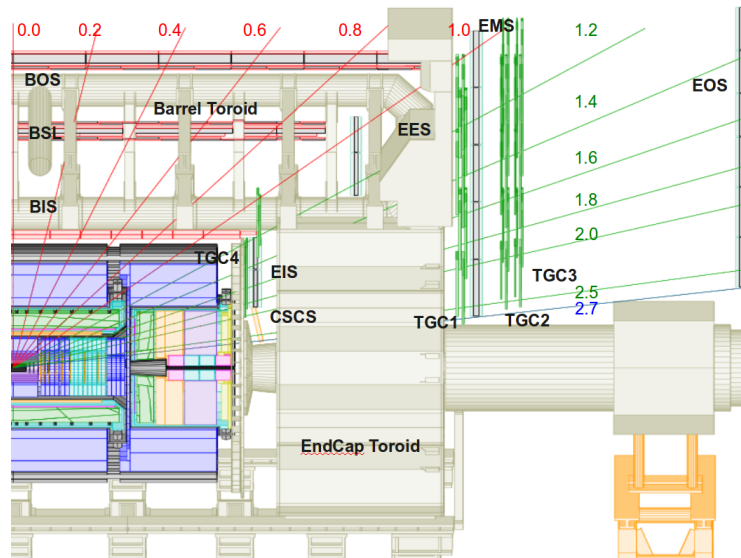


Figure 2.14: Transversal section of the Muon Spectrometer: dotted lines demonstrate how the Extra Endcap chambers provide an extra layer of detection for some particle trajectories and an η coverage up to 2.7.

Table 2.3: Main parameter of the ATLAS muon chambers.

Drift tubes: - Coverage - Number of chambers - Number of chambers - Function	MDTs $ \eta < 2.0$ 1170 354000 Precision measurement
Cathode Strip Chambers: - Coverage - Number of chambers - Number of chambers - Function	CSCs $2.0 < \eta < 2.7$ 32 31000 Precision measurement
Resistive Plate Chambers: - Coverage - Number of chambers - Number of chambers - Function	RPCs $ \eta < 1.05$ 1112 374000 Triggering, second coordinate
Thin Gap Chambers: - Coverage - Number of chambers - Number of chambers - Function	TGCs $1.05 < \eta < 2.4$ 1578 322000 Triggering, second coordinate

the barrel region, the muon sub-detectors are mounted on three concentric cylinders with their axis that coincide with the beam axis at radii of about 5, 7.5 and 10 m.

Groups of three chambers at different radius forms projective towers that point to the interaction position. With this geometry, muons coming from the interaction point will cross at least three precision chambers thus to measure the particle momentum from the measurement of the trajectory sagitta.

In the endcap regions, the detector chambers are placed in four concentric disks located at ~ 7 , ~ 12 and ~ 22 m away from the interaction point.

Along the azimuthal direction the spectrometer is divided in 16 sectors and their dimension depends on if they are between two coils of the toroidal magnet (Large Sectors) or if they contain only one of the coils (Small Sectors).

2.4.3.1 The Monitored Drift Chambers (MDT)

The Monitored Drift Chambers (MDT) cover the rapidity region $|\eta| \leq 2.0$ of the muon spectrometer. The basic elements of these chambers are tubes with a diameter of 29.97 mm filled with Ar/CO_2 gas mixture (93/7) at the

pressure of 3 bar.

When a muon crosses the tube, the electrons generated in the ionization of the gas are collected at the central tungsten-rhenium wire that has a diameter of $50\ \mu\text{m}$ and is maintained at a potential of 3080 V in order to work in the avalanche regime; at this working point, the maximum drift time is around 700 ns.

The gas mixture used for this detector has been chosen for the good ageing properties but has the disadvantage of a non linear space-drift time relation; this leads to a reduction of the spatial resolution in a high counting rate that has been measured to be around $70 - 80\ \mu\text{m}$ per tube.

The tubes are arranged in 2×4 monolayers for the inner stations and 2×3 for the outer stations to form a station that can be rectangular in the barrel and trapezoidal in the endcaps.

The two multi-layers of each station are placed on either side of a special support structure (spacer), that ensure the accurate positioning of the tubes with respect to each other. In the case of non vertical chambers, the support structure also slightly bends the tubes of the chambers in order to compensate the gravitational sag of the wires which are not in a vertical position. Moreover deformation are expected to occur and may change with time (due to thermal gradients) and they are monitored by an in-plane optical system that have its component mounted on the spacers.

2.4.3.2 Cathode Strip Chambers (CSC)

The Cathode Strip Chambers are multi-wire proportional chambers with the wires oriented in the radial direction. They use a gas mixture of Ar/CO_2 (80/20) and work at an operating voltage of 1900 V combining high spatial, time and double track resolution with high-rate capability and low neutron sensitivity.

CSCs are used to substitute the MDT in the innermost layer of the endcap region in the pseudo-rapidity range of $2.0 \leq |\eta| \leq 2.7$ where rates higher than the MDT rate capability (safe operation up to $150\ \text{Hz}/\text{cm}^2$) are reached.

The whole CSC system consists of two disks with eight chambers each (eight small and eight large).

The cathodes are segmented, one with the strips perpendicular and the other parallel to the wires. The cathode-anode spacing is equal to the anode wire pitch ($2.54\ \text{mm}$) and the position of the track is then obtained by interpolation between the charges induced on neighbouring cathode strips.

The read out pitch of $5.31\ \text{mm}$ and $5.56\ \text{mm}$ for the large and small chambers respectively in the bending direction allows to reach a $60\ \mu\text{m}$ resolution for each CSC plane. In the non-bending direction the resolution is $5\ \text{mm}$.

2.4.3.3 Resistive Plate Chambers (RPC)

The Resistive Plate Chambers (RPC) are gaseous detectors made of two resistive plates of phenoli-melaminic plastic laminate with a volume resistivity of $10^{10} \Omega \text{ cm}$ that are kept at an inter-distance of 2 mm by insulating spacers and with the outside surface coated with a thin layer of graphite paint ($100 \text{ k}\Omega/\text{cm}$) to assure the HV and the ground connection of the resistive electrodes.

The volume is filled with a gas mixture of $C_2H_2F_4/Is-C_4H_{10}/SF_6$ (94.7/5/0.3) non flammable that permits to work in avalanche mode and offers the benefit of a high rate capability (the local rate capability is about $\sim 1 \text{ kHz/cm}^2$). In order to have a formation of avalanche along the ionising track, an electric field of 4.9 kV/mm is applied. The signal produced is read out thanks to the capacitive coupling to copper strips that are mounted on the outer faces of the resistive plates.

The RPCs are used in the barrel region $|\eta| \leq 1.05$ to provide the muon trigger and to measure the second coordinate in the non bending direction and they are arranged in three concentric cylindrical layers around the beam axis.

The inter-distance between the middle and outer layers permits the trigger to select tracks with $9 \text{ GeV} < p_T < 35 \text{ GeV}$ while the two middle chambers provide the low- p_T trigger ($6 \text{ GeV} < p_T < 9 \text{ GeV}$).

An RPC chamber is composed by two rectangular detector units that are contiguous to each other; each unit is then composed by two independent detector layers identical for all the RPCs.

2.4.3.4 Thin Gap Chambers (TGC)

The Thin Gap Chambers (TGC) are mounted in two concentric rings located in the endcap regions and covers the rapidity range between $1.05 \leq |\eta| \leq 2.0$. This detector provides the muon trigger capability in the endcap regions and the determination of the second, azimuthal coordinate to complement the measurement of the MDT in the bending (radial) direction.

TGCs have a structure very similar to the one of the multiwire proportional chamber, with the difference that the anode wire pitch (1.8 mm) is larger than the anode-cathode distance (1.4 mm). The cathodic strips are separated from the gas volumes with graphite layers and have a pitch that goes from 14.6 and 49.1 mm with an orientation that is orthogonal to the anodic wires.

The gas mixture used is CO_2 at 55% and $n-C_5H_{12}$ (n-pentane) at 45% thus to work in a quasi-saturated mode (gain $\sim 3 \times 10^5$) with the advantage to have a lower sensibility to the mechanic deformations. The voltage working point of the TGC is 2.9 kV .

2.5 Particle identification, trigger efficiency and reconstruction

A particle passing through the detector can be identified combining all the informations coming from the tracking devices, the calorimeters, and by detecting radiation emitted by charged particles.

Electrons are reconstructed using information from the ID and the electromagnetic calorimeter. For electrons, the background discrimination relies on the shower shape information available from the highly segmented LAr EM calorimeter, high-threshold TRT hits, as well as compatibility of the tracking and calorimeter information.

Muons are reconstructed as tracks in the ID and MS, and their identification is primarily based on the presence of a matching track or tag in the MS.

Finally, jets are reconstructed from clusters of calorimeter cells and calibrated using a dedicated scheme designed to adjust the energy measured in the calorimeter to that of the true jet energy on average.

Leptons are key to some of the most important physics results published by the ATLAS experiment at the LHC. These results include the discovery of the Higgs boson and the measurement of its properties, the precise measurement of Standard Model processes, and searches for physics beyond the Standard Model.

2.5.1 Muon identification and reconstruction

The performance of the ATLAS muon reconstruction during the LHC run at $\sqrt{s} = 13$ TeV has been slightly improved with respect to Run 1, since, during the 2013-2015 shutdown, the ATLAS detector was equipped with additional muon chambers in the transition region between the barrel and the end-caps ($1.0 < |\eta| < 1.4$) and a new innermost Pixel layer (the Insertable B-Layer, IBL), providing measurements closer to the interaction point.

Measurements of the muon reconstruction and isolation efficiencies and of the momentum scale and resolution are carried out comparing data and Monte Carlo (MC) simulation.

Muons are primarily identified and reconstructed by combining information from the ID and MS detectors: about 96% of muons are reconstructed by fitting hits from ID and MS tracks, producing combined muons; the remainder are formed by tagging ID tracks with muon signatures in the calorimeter or the MS.

Muon reconstruction in the MS starts with a search for hit patterns inside each muon chamber to form segments. The MDT segments are reconstructed by performing a straight-line fit to the hits found in each layer; the RPC and TGC hits provide measurements of the coordinate orthogonal to the bending plane and segments in the CSC detectors are built using a separate combinatorial search in the η and ϕ detector planes.

Muon track candidates are then built by fitting together hits from segments in different layers.

The combined ID-MS muon reconstruction is performed according to various algorithms based on the information provided by the ID, MS, and calorimeters in order to provide the best performance in terms of resolution over the entire p_T range.

Muon identification is performed by applying quality requirements that suppress background, mainly from pion and kaon decays, while selecting prompt muons with high efficiency and/or guaranteeing a robust momentum measurement.

To achieve high purity, efficiency and momentum resolution, four types of muons are defined : combined, stand-alone, segment tagged and calorimeter tagged muons (Figure 2.15).

- Combined Muons (CB): muon spectrometer and inner detector hits are fitted to perform a muon track. Combined muons are the standard muon objects for physics analysis and provide candidates of highest purity.
- Segment Tagged Muons (ST): if the hits in the muon spectrometer are not sufficient for a proper measurement, an inner detector track is still considered a SA muon, if the extrapolated track can be associated with a reconstructed muon segment. Segment tagged muons are used to recover low detector efficiencies at low- p_T and badly covered η regions.
- Stand-Alone Muons (SA) or Extrapolated Muons (ME): only the hits in the muon spectrometer are used to reconstruct the track. Its parameters are extrapolated through the calorimeters and the inner detector, energy losses taken into account, back to the beam axis. Those muons are mainly used to extend the acceptance in the region $2.5 < |\eta| < 2.7$ which is not covered by the ID.
- Calorimeter Tagged Muons (CT): a trajectory in the ID is identified as a muon if the associated energy depositions in the calorimeters are compatible with the hypothesis of a minimum ionizing particle (MIP). This muon type has the lowest purity of all, but it is used to recover the acceptance in the region $|\eta| < 0.1$ where the ATLAS MS is only partially instrumented to allow for cabling and services.

When two muon types share the same ID track, preference is given to CB muons, then to ST, and finally to CT muons. The overlap with ME muons in the muon system is resolved by analyzing the track hit content and selecting the track with better fit quality and larger number of hits.

The inner detector measurement dominates the combination up to $p_T = 80$ GeV in the barrel and $p_T = 20$ GeV in the end-caps. For transverse

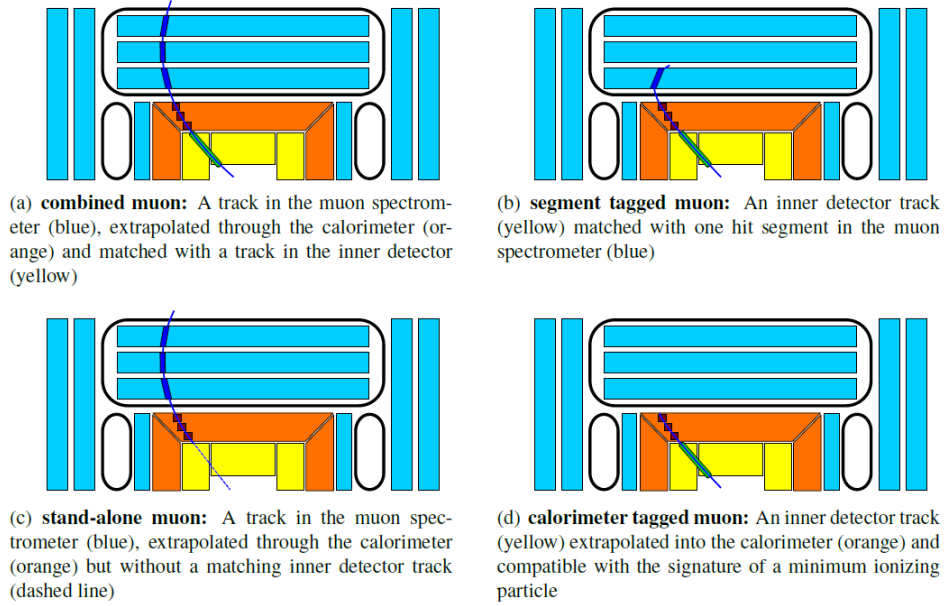


Figure 2.15: The four types of muon candidates defined at ATLAS: combined (a), segment tagged (b), stand-alone (c) and calorimeter tagged (d) [9].

momenta up to 100 GeV the inner detector and muon spectrometer measurements have similar weights while the muon spectrometer dominates at $p_T \geq 100$ GeV.

The relative momentum resolution, $\sigma(p)/p$, originates from different effects. The ATLAS MS is designed to provide a momentum resolution as a function of the η and ϕ ; therefore, for a given value of η , the resolution can be parametrized as a function of p_T :

$$\frac{\sigma(p)}{p} = \frac{p_0^{MS}}{p_T} \oplus p_1^{MS} \oplus p_2^{MS} p_T \quad (2.9)$$

where p_0^{MS} , p_1^{MS} and p_2^{MS} are coefficients related to the energy loss in the calorimeter, multiple scattering and intrinsic resolution terms, respectively. For the ID, the curvature measurement depends on the track length of the muon in the active material, which is reduced close to the edge of the TRT fiducial volume. This results in a uniform response in the central part and a rapid worsening beyond this region. The approximate parametrization of the resolution is therefore:

$$\frac{\sigma(p)}{p} = p_1^{ID} \oplus p_2^{ID} p_T \quad \text{for } |\eta| < 1.9 \quad (2.10)$$

$$\frac{\sigma(p)}{p} = p_1^{ID} \oplus p_2^{ID} p_T \frac{1}{\text{tg}^2(\theta)} \quad \text{for } |\eta| > 1.9 \quad (2.11)$$

where p_1^{ID} and p_2^{ID} are the multiple scattering and the intrinsic resolution terms, respectively.

The parametrized resolution as a function of p_T for the barrel region, obtained using the values of the parameters from the combined fits, are shown in Figure 2.16 for the MS and the ID.

The resolution curves for experimental data (in blue) are compared to those from uncorrected parameters obtained for the simulation (in red).

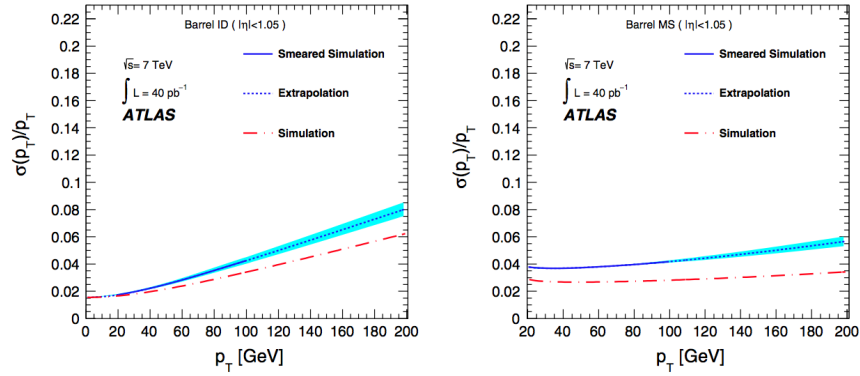


Figure 2.16: Resolution curve from the fitted parameter values on the ID (left) and the MS (right) in collision data and simulation as a function of the muon p_T , for the barrel region. The solid blue line shows determinations based on data, the dashed blue line shows the extrapolation to p_T range not accessible in this analysis and the dashed red line shows the determinations from simulation [10].

The reconstruction efficiency for combined muons is the product of three independent sub-efficiencies:

$$\epsilon_{reco} = \epsilon_{ID} \times \epsilon_{MS} \times \epsilon_{match} \quad (2.12)$$

where ϵ_{ID} is the efficiency that the inner tracking system reconstructs a track from the muon, ϵ_{MS} is the efficiency of the muon spectrometer reconstructing a track from the muon and ϵ_{match} is the efficiency of combining the two tracks to a combined one. To determine these efficiencies, a so called *Tag and Probe* method is used.

With stringent selection criteria on the tag object's side and the correlation to the probe, one can ensure the identity of the probe object without direct, hard cuts on this object.

Since the Z boson decays to $\mu^+\mu^-$ provide us a excellent muon source with low background it is therefore used to perform the muon efficiency measurement with the Tag-Probe method. The tag and probe muons are consecutively combined and further pair criteria are applied. They have to be of opposite charge, originate from the same vertex and their invariant mass has

to be within a range around the nominal Z boson mass value. Finally, the probe track is used to calculate the muon reconstruction efficiency (Figure 2.17):

$$\epsilon_{reco} = \frac{\# \text{ of probes matched with } CB - ST \text{ muons}}{\# \text{ of total probes}} \quad (2.13)$$

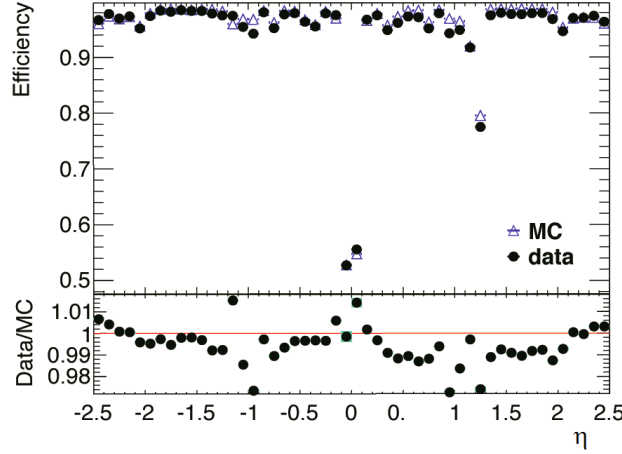


Figure 2.17: Efficiency computed using $Z \rightarrow \mu^+ \mu^-$ Tag and Probe technique. The inefficiency at $\eta = 0$ is due to the absence of muon chambers in that region.

Four different muon identification selections (*Medium*, *Loose*, *Tight*, and *High- p_T*) are provided to address the specific needs of different physics analyses (this muon identification selection have been added in Run2 and were not present in Run1). *Loose*, *Medium*, and *Tight* are inclusive categories in that muons identified with tighter requirements are also included in the looser categories.

- The *Medium* identification criteria provide the default selection for muons in ATLAS. Only CB and MS tracks are used. The former are required to have ≥ 3 hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. The latter are required to have at least three MDT/CSC layers, and are employed only in the $2.5 < |\eta| < 2.7$ region to extend the acceptance outside the ID geometrical coverage. A loose selection on the compatibility between ID and MS momentum measurements is applied to suppress the contamination due to hadrons misidentified as muons. Specifically, the q/p significance is required to be less than seven. In the pseudorapidity region $|\eta| < 2.5$, about 0.5% of the muons classified as *Medium*

originate from the inside-out combined reconstruction strategy. This selection minimises the systematic uncertainties associated with muon reconstruction and calibration.

- The *Loose* identification criteria are designed to maximise the reconstruction efficiency while providing good-quality muon tracks. They are specifically optimised for reconstructing Higgs boson candidates in the four-lepton final state. All muon types are used. All CB and ME muons satisfying the *Medium* requirements are included in the *Loose* selection. CT and ST muons are restricted to the $|\eta| < 0.1$ region. In the region $|\eta| < 2.5$, about 97.5% of the *Loose* muons are combined muons, approximately 1.5% are CT and the remaining 1% are reconstructed as ST muons.
- *Tight* muons are selected to maximise the purity of muons at the cost of some efficiency. Only CB muons with hits in at least two stations of the MS and satisfying the *Medium* selection criteria are considered. The normalised χ^2 of the combined track fit is required to be < 8 to remove pathological tracks. A two-dimensional cut in the ρ' and q/p significance variables is performed as a function of the muon p_T to ensure stronger background rejection for momenta below 20 GeV where the misidentification probability is higher.
- The *High- p_T* selection aims to maximise the momentum resolution for tracks with transverse momentum above 100 GeV. The selection is optimised in particular for searches for high-mass Z' and W' resonances. CB muons passing the *Medium* selection and having at least three hits in three MS stations are selected. Specific regions of the MS where the alignment is suboptimal are vetoed as a precaution. Requiring three MS stations, while reducing the reconstruction efficiency by about 20%, improves the p_T resolution of muons above 1.5 TeV by approximately 30%.

2.5.2 Electron identification and reconstruction

In the ATLAS detector, electrons and positrons, collectively referred to as electrons, in the central region give rise to tracks in the inner detector and energy deposits in the electromagnetic calorimeter.

The electron candidates are then further selected against background such as hadrons and background (non-prompt) electrons originating predominantly from photon conversions and heavy flavour hadron decays using several sets of identification criteria with different levels of background rejection and signal efficiency.

These identification criteria rely on the shapes of electromagnetic showers in the calorimeter as well as on tracking and track-to-cluster matching

quantities. Additionally, electrons can be required to be isolated from other activity in the calorimeter or inner detector to further distinguish them from background objects.

The accuracy of the Monte Carlo (MC) detector simulation to model the electron measurement efficiency plays a crucial role for cross section measurements and searches for new physics.

In order to achieve reliable results, the MC samples are corrected to reproduce the efficiencies measured with data. The efficiency measurements of the various steps described above (trigger, reconstruction, identification and isolation) are based on the tag-and-probe method using the Z and the J/Ψ resonances, requiring the presence of an isolated identified electron as the tag. The data measurements are compared to the simulation to obtain corrections (scale-factors) as a function of the electron's transverse energy E_T and its pseudorapidity η .

To determine whether the reconstructed electron candidates are signal-like or background-like objects (like hadronic jets or converted photons), algorithms for electron identification (ID) are applied. The ID algorithms use quantities related to the electron cluster and track measurements and variables measuring bremsstrahlung effects in order to distinguish signal from background: these quantities are summarised in Figure 2.18. For Run-2, taking advantage of the IBL, the number of hits in this innermost pixel layer has been used for discriminating between electrons and converted photons. This criterion was also used in Run-1, but with what is now the second-to-innermost pixel layer. Moreover, the change in the TRT gas³ led to modifications in the detector response and prompted the introduction of a new discriminating variable in the electron identification algorithms. In Run-1, only the fraction of high-threshold hits was used from the TRT as a signature of transition radiation to distinguish electrons from hadrons. In Run 2, a likelihood method based on the TRT high-threshold hits is introduced to compensate for the lower transition radiation absorption probability of the argon.

In addition to the variables used as input to the Likelihood (LH) discriminant, simple selection criteria are used for the variables counting the number of hits on the track.

Three levels of identification operating points are typically provided for electron ID. These are referred to, in order of increasing background rejection, as *Loose*, *Medium*, and *Tight*.

The *Loose*, *Medium* and *Tight* operating points are defined such that the samples selected by them are subsets of one another; each operating point uses the same variables to define the LH discriminant, but the selection on

³Significant modifications of the TRT detector have been made for LHC Run2 to improve the response to the expected much higher rate of hits and to mitigate leaks of the Xe-based active gas mixture. Many gas leaks were repaired and the gas system was modified to use a cheaper Ar-based gas mixture in some channels.

Type	Description	Name
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	R_{had1}
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}
Back layer of EM calorimeter	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter. This variable is only used below 100 GeV because it is known to be inefficient at high energies.	f_3
Middle layer of EM calorimeter	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_ϕ
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_η
Strip layer of EM calorimeter	Shower width, $\sqrt{(\sum E_i (i - i_{max})^2)/(\sum E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in η , and i_{max} is the index of the highest-energy strip	w_{stot}
	Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies	E_{ratio}
	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter	f_1
Track conditions	Number of hits in the innermost pixel layer; discriminates against photon conversions	n_{Blayer}
	Number of hits in the pixel detector	n_{Pixel}
	Number of total hits in the pixel and SCT detectors	n_{Si}
	Transverse impact parameter with respect to the beam-line	d_0
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	d_0/σ_{d_0}
	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum	$\Delta p/p$
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	$\Delta\eta_1$
	$\Delta\phi$ between the cluster position in the middle layer and the track extrapolated from the perigee	$\Delta\phi_2$
	Defined as $\Delta\phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track from the perigee to the middle layer of the calorimeter	$\Delta\phi_{res}$
	Ratio of the cluster energy to the track momentum	E/p

Figure 2.18: Definitions of electron discriminating variables.

this discriminant is different for each operating point:

- *Loose* criteria contains cuts on the detector acceptance and the hadronic leakage as well as constraints on the shower shapes in the second sampling of the calorimeter.
- *Medium* criteria is stricter than loose, requiring in addition cuts on the first sampling shower shape variables and on the quality of the tracks (number of hits in the Pixels, SCT, and impact parameter).
- *Tight* criteria implies additional identification cuts which test the energy and momentum agreement (E/p) and make use of the TRT detector signal.

The distributions of electron shower shapes depend on the amount of material the electrons pass through, and therefore vary with the pseudo-rapidity of the electron candidates. In addition, significant changes to the shower shapes and track properties are expected with increasing energy. The ID operating points were consequently optimized in several bins in $|\eta|$ and E_T . The performance of the LH identification algorithm is illustrated in Figure 2.19.

Depending on the operating point, the signal (background) efficiencies for electron candidates with $E_T = 25$ GeV are in the range from 78 to 90% (0.3 to 0.8%) and increase (decrease) with E_T .

In addition to the multivariate approach used in the LH method, a cut-based method using a set of rectangular cuts on the electron ID discriminating variables was used in Run 1. This method encompasses a similar set of operating points. The cut-based *Loose* operating point relies primarily on information from the hadronic calorimeter and the first two layers of the EM calorimeter in order to distinguishing signal from background. The cut-based *Medium* operating point adds information from the TRT, the transverse impact parameter, and the third layer of the EM calorimeter, in addition to tighter cuts on the variables from the cut-based *Loose* ID. Finally, the cut-based *Tight* operating point adds track-cluster matching variables such as E/p and $\Delta\Phi_2$, and uses tighter cuts than the cut-based *Medium* ID for the remaining variables.

The cut-based algorithms were optimised for Run 2 and used as for cross-checks. In addition to the identification criteria described above, most analyses require electrons to fulfil isolation requirements, to further discriminate between signal and background. The isolation variables quantify the energy of the particles produced around the electron candidate and allow to disentangle prompt electrons (from heavy resonance decays, such as $W \rightarrow e\nu$, $Z \rightarrow ee$) from other, non-isolated electron candidates such as electrons originating from converted photons produced in hadron decays, electrons from heavy flavour hadron decays, and light hadrons misidentified as electrons. Two discriminating variables have been designed for that purpose:

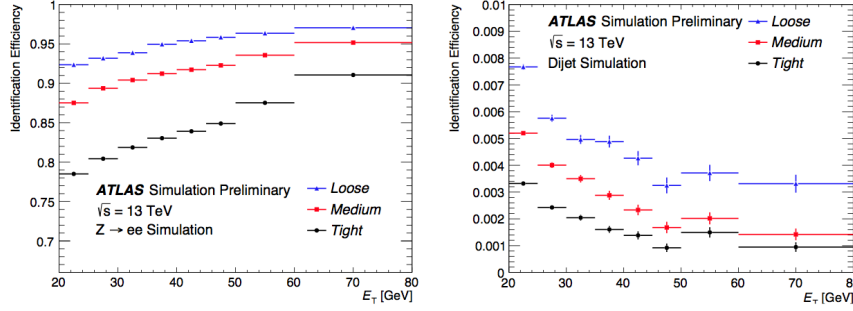


Figure 2.19: The efficiency to identify electrons from $Z \rightarrow ee$ decays (left) and the efficiency to identify hadrons as electrons (background rejection, right) estimated using simulated dijet samples. The efficiencies are obtained using Monte Carlo simulations, and are measured with respect to reconstructed electrons. The candidates are matched to true electron candidates for $Z \rightarrow ee$ events. For background rejection studies the electrons matched to true electron candidates are not included in the analysis. Note that the last bin used for the optimisation of the ID is 45 – 50 GeV, which is why the signal efficiency increases slightly more in the 50 GeV bin than in others, and the background efficiency increases in this bin as well.

- a calorimetric isolation energy, $E_T^{cone0.2}$, defined as the sum of transverse energies of topological clusters, calibrated at the electromagnetic scale, within a cone of $\Delta R = 0.2$ around the candidate electron cluster;
- track isolation, $p_T^{varcone0.2}$, defined as the sum of transverse momenta of all tracks, satisfying quality requirements, within a cone of $\Delta R = \min(0.2, 10 \text{ GeV}/E_T)$ around the candidate electron track and originating from the reconstructed primary vertex of the hard collision.

A variety of selection requirements on the quantities $E_T^{cone0.2}/E_T$ and $p_T^{varcone0.2}/E_T$ have been defined to select isolated electron candidates. The resulting typical isolation efficiency (ϵ_{iso}) is 90(99)% for $E_T = 25(60)$ GeV, estimated for electrons from simulated $Z \rightarrow ee$ events. For transverse energies between 7 and 15 GeV, simulated electrons from J/Ψ decays have been used to determine the upper cuts on $E_T^{cone0.2}$ and $p_T^{varcone0.2}$, and only events satisfying $\Delta\phi > 0.3$ have been considered, where $\Delta\phi$ is the azimuthal separation between the two electrons.

The efficiency of identification criteria is given in Table 2.4, together with the corresponding rejection power against jets.

The overall efficiency has been stabilized as a function of η for loose and medium cuts. For the tight criteria, the losses are caused by the deterioration of the electron reconstruction as the amount of material in front of the calorimeter increases. This affects the stricter cluster-track matching required by the tight criteria, especially at low transverse momenta and high

Table 2.4: Electron efficiency computed using $Z \rightarrow ee$ sample and jet rejection for $E_T > 17$ GeV.

Cuts	$E_T > 17$ GeV	$E_T > 17$ GeV
	Efficiency [%]	Jet rejection
Loose	87.96 ± 0.07	567 ± 1
Medium	77.29 ± 0.06	2184 ± 13
Tight	61.66 ± 0.07	$(8.9 \pm 0.3) 10^4$

pseudo-rapidity.

Figure 2.20 shows the electron reconstruction efficiency as a function of η and E_T .

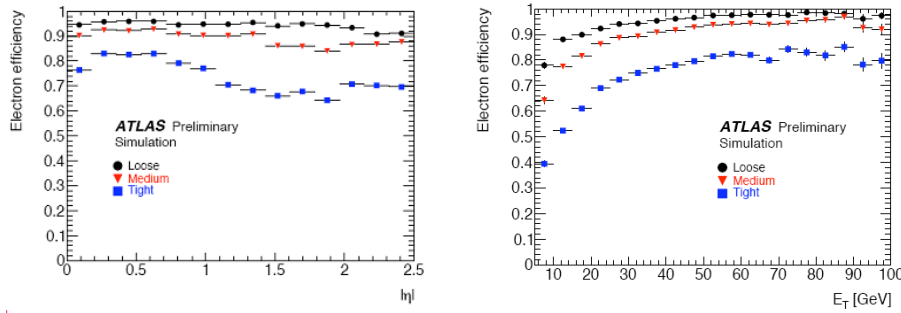


Figure 2.20: Electron reconstruction efficiencies after optimization as a function of p_T and η [11].

2.5.3 Trigger system

The Trigger system at the design luminosity the proton-proton interaction rate is of the order of 1 GHz , considering an interaction rate of 40 MHz and 23 interactions per bunch crossing.

Due to the fact that most of the events are not interesting for physics analysis and to the limited storage capacity and computing power, a trigger system has been designed for the ATLAS experiment to trim this rate down to a more manageable data flow.

It is organized in three level: each trigger level refines the decision made by the previous level and it is based on fast and crude reconstruction of physics object like muons, electrons, photons, jets.

- The Level 1 trigger (LVL1) is the first level of the ATLAS trigger chain, it is an hardware-based trigger and makes a first selection using: the RPC and TGC chambers to identify muons with high transverse momenta; the calorimeters for high E_T photons and electrons, jets, τ

decaying into hadrons. Moreover, the calorimetric information (with reduced granularity) is used to measure the total and missing transverse energy. Cuts on the energy and p_T are applied and events that pass the LVL1 trigger selection are transferred to the next trigger level. The output rate of the LVL1 trigger cannot exceed the 75 kHz with a maximum latency of $2.5\text{ }\mu\text{s}$ required to make the final decision. During this time, the information coming from all the detector is temporary saved in local memories with a limited extension (pipelines) that are mostly located in integrated circuits near the detectors. In addition the LVL1 trigger defines one or more Regions-of-Interest (RoIs) corresponding to $\eta - \phi$ region of the detector where the object that pass a certain trigger item is present, that will be given to the second level of the trigger.

- The Level 2 trigger (LVL2) is a software-based trigger that is seeded by the RoI information provided by the LVL1 trigger. The information with full granularity and precision is used to reconstruct within a RoI only the events that satisfy a certain set of selection on the measured quantities of physics object pass this trigger level. The trigger rate is reduced to approximately 2 kHz , with an event processing time of about 40 ms .
- The Event Filter (EF) is the final stage of the trigger selection and it is carried on by the Event Filter, which roughly reduces the event rate to 200 Hz . Here only events that pass at least one of the LVL2 trigger algorithm are processed. This level have access to the whole event, using the full granularity and all the ATLAS detector information. The EF use the off-line analysis procedure, such as detailed reconstruction algorithms and the mean processing time for one event at the event filter is ~ 4 seconds. This last step of the ATLAS trigger runs on a dedicated computer farm that is located near the ATLAS cavern and the events that pass this final stage are written to the mass storage and available for the further off-line analysis.

The second and third trigger levels are referred to collectively as the High-Level Trigger (HLT) system; they share an overall trigger selection framework, and differ mostly in the amount of event data they access and how they access it as well as in the complexity and speed of the algorithms.

While the LVL1 uses only coarse-grained calorimeter and muon information, the second-level trigger (LVL2) can use full-resolution, full-granularity data from all detectors and combine the information from different sub-detectors for the first time. In practice, the LVL2 trigger restricts itself to so-called Regions of Interest (RoIs): small regions in pseudo-rapidity - azimuth space ($\eta - \phi$) centred on objects identified by LVL1.

2.5.4 Muon Trigger

The muons accepted by the LVL1 trigger include a high rate of muons from π and K decaying in flight, many of which have true p_T below the nominal threshold.

The first step of the High Level Trigger (HLT) muon trigger is to try to confirm the LVL1 muons and reject fakes. The algorithm uses MDTs in addition to RPCs and TGCs, and achieves a p_T resolution of about 5.5 % at low p_T and about 4 % in the high p_T case.

The trigger efficiency is then about 90 % for muons with p_T above the trigger threshold.

The muon-spectrometer algorithm reduces the LVL1 rate by factors of 2(10) for the low(high)- p_T cases respectively.

A further strong rejection is achieved by combining the LVL2 muon spectrometer results with information from the precision tracker; the algorithm takes advantage of the fact that, for those muons originating from π and K decays, the p_T measured in the inner detector and the muon system will differ significantly.

Applying p_T matching criteria achieves another significant reduction compared to the LVL2 muon algorithm alone; then, isolation criteria in the calorimeter can be applied to further reject muons from semi-leptonic b and c decays.

The tag and probe method was also used to measure the trigger efficiency relative to reconstructed muons.

The trigger efficiency measurement follows the same approach as the measurement of the reconstruction efficiency, with the main difference being that reconstructed muons are used as a probe.

Two kinds of trigger efficiencies are measured:

- $\epsilon(LVL1 | rec)$: the probability for a reconstructed muon to pass the level 1 trigger;
- $\epsilon(LVL2 \& EF | LVL1 \& rec)$: the probability for a reconstructed muon accepted by the LVL1 trigger to pass a particular p_T threshold at level 2 and in the Event Filter.

Figure 2.21 shows $\epsilon(LVL1 | rec)$ for the lowest LVL1 threshold (“LVL1_MU0”) with respect to chain 1 muons for the regions covered by the RPC ($|\eta| < 1.05$) and the TGC ($1.05 < |\eta| < 2.4$) trigger chambers. The efficiency at plateau ($p_T > 8$ GeV) is ~ 80 % (76 %) for CB (CB+ST) muons in the barrel and ~ 95 % (93 %) in the end-cap.

The lower efficiency in the barrel region is mainly due to the geometrical acceptance of the trigger systems that have inefficient regions corresponding to support structures of the ATLAS detector. The LVL1 efficiency for CB muons is higher than for $CB + ST$ muons, in particular at low p_T . This is

because the LVL1 trigger chambers are placed close to the second layer of MDT chambers in the MS. CB muons, that require segments in at least two MDT layers to be reconstructed, are typically made of muons that reach the middle stations, while ST muons, at low p_T , are typically made of muons reaching only the inner MDT stations, therefore missing the trigger chambers.

The efficiency $\epsilon(LVL2\&EF|LVL1\&rec)$ is shown in Figure 2.22 for two p_T thresholds, $p_T > 4$ GeV (“EF mu4”) and $p_T > 6$ GeV (“EF mu6”).

The efficiency above the nominal threshold is 90 % or larger.

Muons from J/ψ decays have been used to measure the reconstruction and trigger efficiencies of the ATLAS detector for low- p_T muons. The reconstruction efficiency is well described by the Monte Carlo simulation and for $p_T > 6$ GeV it is above 98 % and the scale factor, defined as the ratio of data-to-MC efficiencies, ranges from 0.98 to 1.01 depending on the particular type of reconstruction considered.

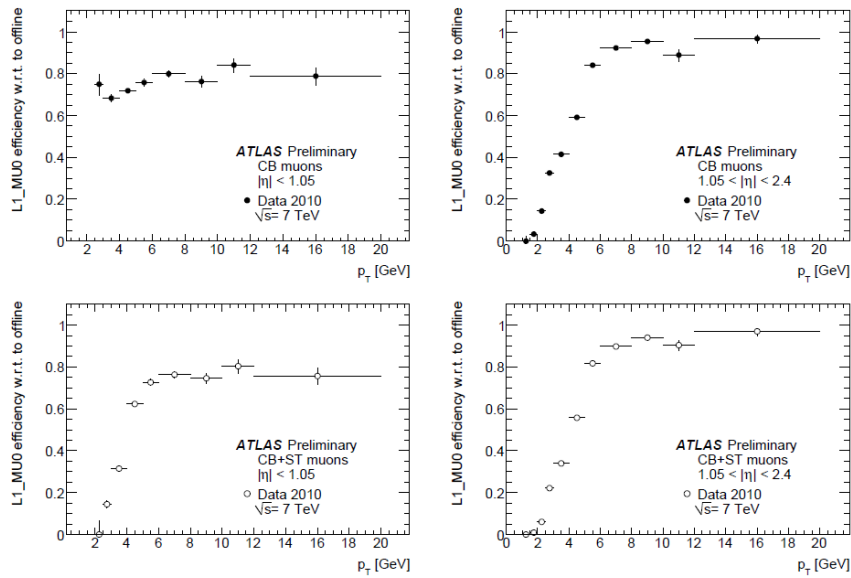


Figure 2.21: Efficiency $\epsilon(LVL1 | rec)$ for the LVL1 trigger “LVL1_MU0” with respect to reconstructed chain 1 muons, CB (upper plots) muons as a function of p_T for the trigger barrel (left) and end-cap (right) regions. The lower plots show the efficiencies for CB + ST muons [12].

2.5.5 Electron trigger

In the first step the LVL1 trigger is used to find clusters in the calorimeter to which transverse-energy and shower-shape criteria are applied: most events are already rejected at this stage.

For electron candidates, a track search in the inner detector close to the

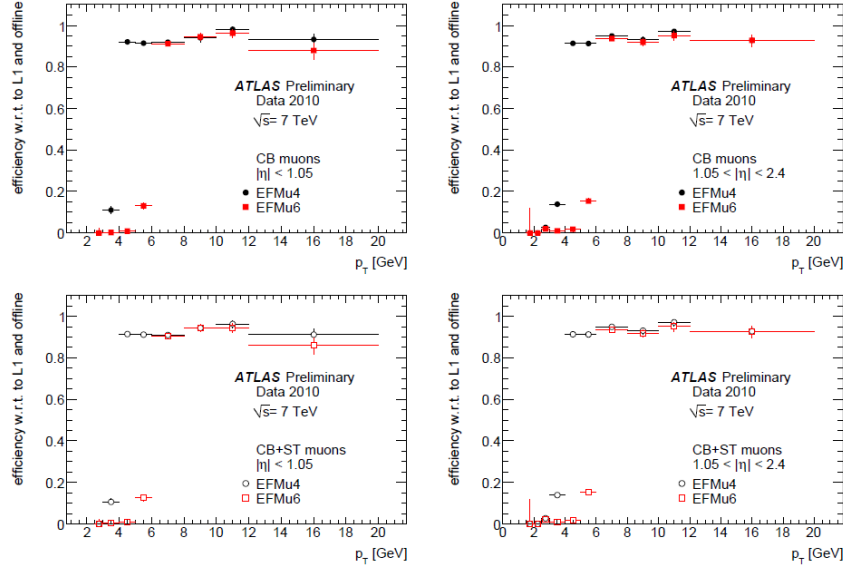


Figure 2.22: Efficiency $\epsilon(LVL2\&EF \mid LVL1\&rec)$ for the LVL2 and Event Filter trigger; p_T thresholds of 4 and 6 GeV with respect to reconstructed chain 1 *CB* (upper plots) and *CB + ST* (lower plots) muons that passed the LVL1 trigger [12].

cluster is then performed: a large rejection against photons from π_0 decays is achieved by requiring matching of energy/momentum and position of cluster and track.

The transition-radiation tracker can be used to further discriminate electrons from pions; Bremsstrahlung recovery for electrons and conversion recovery for photons are further steps which are likely to be performed in the EF.

Although the selection efficiency is generally higher when using the EF for rejection, this has to be weighted against the increased rate and bandwidth out of LVL2 and the computing resources required at the EF level. The common HLT selection software used in both systems provides the flexibility to optimize the overall HLT system taking both physics and system parameters into account.

Starting with an LVL1 EM-cluster trigger rate of about 22 kHz, the HLT reduces this to about 114 Hz.

The electron trigger efficiency is studied with respect to electrons identified by the off-line reconstruction software and, depending on the E_T , different estimation of the trigger efficiency are reported.

- **Low- E_T ($E_T < 15$ GeV):** the trigger efficiencies are computed using $J/\Psi \rightarrow ee$ events since they provide a well known signature. The tag and probe method is used, which requires a single off-line electron, the tag, to pass a particular trigger. Any remaining off-line

electrons in the event can be used to probe the efficiency of other triggers. For the J/Ψ study, the tag and probe electrons must each satisfy the off-line tight-selection and, together, have an invariant mass within $2.6 \text{ GeV} < m_{ee} < 3.2 \text{ GeV}$.

Additional quality cuts are applied to the two electrons in order to ensure quality tracks in the inner detector and no contamination from fake electrons. The probe-electron is used to measure the *e5_tight* trigger efficiency, which reaches a plateau at approximately 7 GeV and the integrated LVL2 and EF efficiencies measured on data above this threshold are 97.0 % and 94.0 % respectively.

- **High- E_T (W events):** the electron trigger efficiencies are computed using $W \rightarrow e\nu$ events since they offer a high statistics sample. The technique used is similar to the tag and probe method: the $W \rightarrow e\nu$ events are tagged by the neutrino, using E_T^{miss} , and the probe is the electron. The event is required to pass E_T^{miss} triggers with thresholds between 20 and 40 GeV. To purify the sample, the event is required to have $E_T^{miss} > 25 \text{ GeV}$, isolated with respect to jet activity and $m_T > 40 \text{ GeV}$ to reduce contamination from fakes.

The probe (electron) is required to pass the off-line tight-selection, and the background is subtracted using a data-driven method.

Figure 4.37 shows the efficiency of the *e15_medium* trigger with respect to off-line tight electrons as a function of the off-line electron E_T and η .

The plateau of the turn-on curve is reached at about 20 GeV, above which the *e15_medium* efficiency is $99.08 \pm 0.04\%(\text{stat.}) \pm 0.10\%(\text{syst.})$. The efficiency for the *e20_loose* trigger where the plateau is reached about 5 GeV above the threshold, i.e. at about 25 GeV. Using the same method, the *e20_loose* trigger efficiency for electrons with $E_T > 25 \text{ GeV}$ is measured to be $99.36 \pm 0.04\%(\text{stat.}) \pm 0.12\%(\text{syst.})$.

- **High- E_T (Z events):** the electron trigger efficiencies are computed using the $Z \rightarrow ee$ decay, which is another *standard candle* in measuring high- E_T electron efficiencies. Similar to the $W \rightarrow e\nu$ analysis, the tag-and-probe technique is employed. Events are selected by requiring two tightly identified electrons with opposite charge and $E_T > 20 \text{ GeV}$, reconstructed by the off-line software. The invariant mass of the electron pair must be between 80 and 100 GeV. The tag must pass the *e15_medium* trigger and match an off-line tight electron with $\Delta R < 0.15$ (in units of η/Φ). The background contamination of the probe sample is negligible when the tight-selection is used.

The efficiencies of the *e15_medium* and *e20_loose* triggers are measured using the $Z \rightarrow ee$ signal and similar E_T and η distributions as those seen in the $W \rightarrow e\nu$ analysis are obtained.

Figure 4.37 directly compares the *e15_medium* and *e20_loose* trigger efficiencies measured in Z events with those measured in W events.

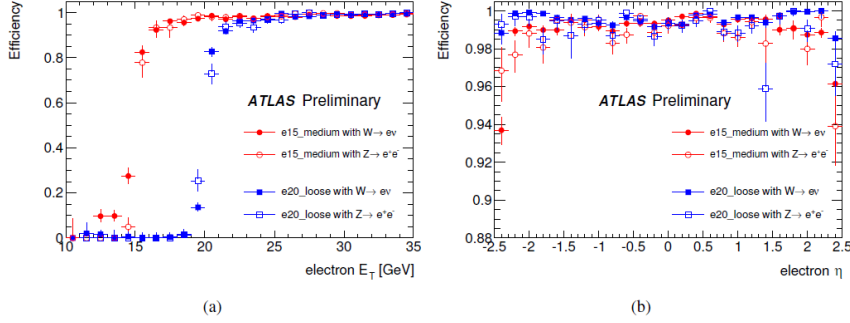


Figure 2.23: Efficiencies for the *e15_medium* and *e20_loose* triggers, measured in $W \rightarrow e\nu$ events, using E_T^{miss} triggers, and $Z \rightarrow ee$ events. The efficiencies are measured at the EF level with respect to the off-line tight electron (a) E_T and (b) η . For the η distribution the electrons are selected with $E_T > 20$ GeV (for *e15_medium*) and with $E_T > 25$ GeV (for *e20_loose*). The uncertainties are statistical only [13].

Chapter 3

The $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e, \mu$) decay channel reconstruction and event selection

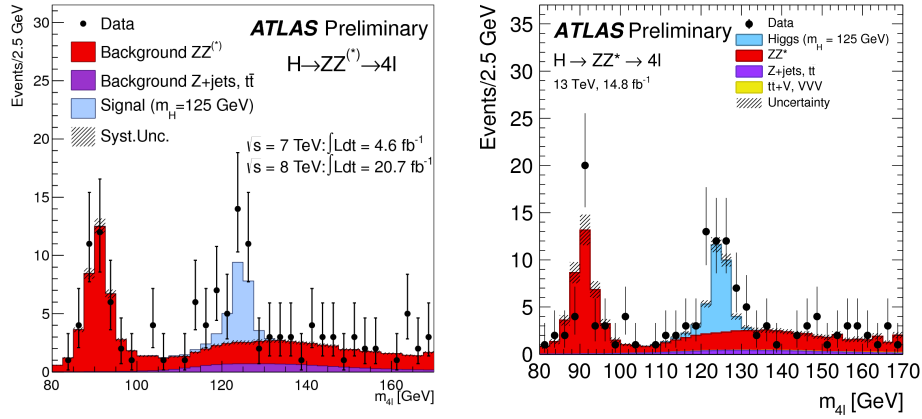


Figure 3.1: The distributions of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates compared to the background expectation for the combined $\sqrt{s} = 7 - 8$ TeV (left) and $\sqrt{s} = 13$ TeV (right) data sets. The signal expectation for the $m_H = 125$ GeV hypothesis is also shown.

Due to its simple signature and excellent mass resolution, the $H \rightarrow ZZ^* \rightarrow 4\ell$ final state has an unambiguous Higgs boson decay signature and this is why it is referred to as the *Golden Channel*.

Although the expected signal yield in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel is very small ($BR_{H \rightarrow ZZ^* \rightarrow 4\ell} = 0.125 \cdot 10^{-3}$, see Chapter 1), it is the only channel which has a signal-over-background ratio above one, hence it will be particularly powerful in the future LHC programme with a larger dataset.

Given the very low branching ratio, it is important therefore to maintain a very high lepton selection efficiency over a broad range of momenta, and also a good 4-lepton mass resolution.

The Higgs decaying in two Z bosons is characterized by the presence of an on-shell Z (with an invariant mass around 91.2 GeV) and an off-shell Z , both decaying in two pair of same flavour, opposite sign, high p_T and isolated leptons.

The main backgrounds to this channel are the SM ZZ^* production, which is irreducible in the sense that it shows the same signature of the $H \rightarrow 4\ell$ signal, and is estimated from Monte Carlo (MC) simulation. The reducible background is instead composed by top-quark production and Z +jets events, which can be suppressed applying isolation and impact parameter requirements.

In this Chapter the data and MC samples used, the selection criteria and the background estimates will be discussed to introduce the measurements performed in the following Chapters.

3.1 Data and Monte Carlo samples

3.1.1 Data sample

The data collected by the ATLAS experiment are subjected to quality requirements, therefore, events recorded during periods when the relevant detector components were not operating properly are rejected. On this purpose, a GoodRuns-List (GRL) is used to record when the detector is fully operational at the granularity of individual luminosity blocks (~ 5 minutes of data-taking).

The resulting integrated luminosity corresponds to 4.6 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$, 20.7 fb^{-1} at 8 TeV and 14.8 fb^{-1} at 13 TeV .

3.1.2 Monte Carlo signal and background samples

The signal MC has been used in order to optimize the analysis selection criteria.

The detector response for all generated events is determined using the ATLAS detector simulation within the GEANT4 framework [14].

The irreducible background estimate is entirely performed using MC while,

concerning the reducible background processes (i.e. $Z + jets$ and $t\bar{t}$) simulation is used in order to determine the efficiency factors for the extrapolation from control regions to the signal region and to provide shapes of variables of interest for the measurements.

Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation.

The MC samples are re-weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data.

Signal samples

The $H \rightarrow ZZ^* \rightarrow 4\ell$ signal is modelled using the POWHEG [15] Monte Carlo (MC) event generator, which calculates separately the gluon fusion (ggF) and vector-boson fusion (VBF) production mechanisms with matrix elements up to next-to-leading order (NLO).

The Higgs boson transverse momentum (p_T) spectrum in the gluon fusion process is re-weighted to include QCD corrections up to NLO and QCD soft-gluon re-summations up to next-to-next-to-leading logarithm (NNLL). POWHEG is then interfaced to PYTHIA [16] for showering and hadronization, which in turn is interfaced to PHOTOS [17] for quantum electrodynamics (QED) radiative corrections in the final state and to TAUOLA [18] for the simulation of tau lepton decays. PYTHIA is used to simulate the production of a Higgs boson in association with a W or a Z boson.

The Higgs boson production cross section for the gluon-fusion process has been calculated to next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) in QCD; QCD soft-gluon resummations calculated in the next-to-next-to-leading logarithm (NNLL) approximation are applied together with NLO electroweak (EW) radiative corrections. The cross sections for the vector-boson fusion process are calculated with full NLO QCD and EW corrections, and approximate NNLO QCD corrections are available.

The MC used for the associated production is PYTHIA at LO, while the cross sections for the associated WH/ZH production processes are calculated at NLO and at NNLO in QCD, and NLO EW radiative corrections are applied.

The Higgs boson decay branching ratio to the four-lepton final state is predicted by PROPHECY4F [21], which includes the complete NLO QCD + EW corrections, the interference effects between identical final-state fermions, and the leading two-loop heavy Higgs boson corrections to the four-fermion width.

Table 1.1 gives the production cross sections and branching ratios for $H \rightarrow ZZ^* \rightarrow 4\ell$.

Background samples

The ZZ^* continuum background is generated using POWHEG for quark-antiquark annihilation and GG2ZZ for gluon fusion.

The POWHEG prediction, including both quark-antiquark annihilation and gluon fusion at QCD NLO, is used for the inclusive total cross section and the shape of the invariant mass of the ZZ^* system (m_{ZZ^*}). The QCD scale uncertainty has a $\pm 5\%$ effect on the expected ZZ^* background, and the effect due to the PDF and α_S uncertainties is about $\pm 4\%$ ($\pm 8\%$) for quark-initiated (gluon-initiated) processes.

The Z+jets production is generated using ALPGEN [23] and is divided into two regions:

- $Z + \text{light jets}$, which includes $Zc\bar{c}$ in the massless c-quark approximation and $Zb\bar{b}$ from parton showers;
- $Zb\bar{b}$ using matrix element calculations that take into account the b-quark mass.

Therefore, $b\bar{b}$ pairs with separation $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.4$ between the b-quarks are taken from the matrix-element calculation, whereas for $\Delta R < 0.4$ the parton-shower $b\bar{b}$ pairs are used.

In this search the Z+jets background is normalized using control samples from data.

For comparisons with simulation, the QCD NNLO FEWZ and MCFM cross section calculations are used for inclusive Z boson and $Zb\bar{b}$ production, respectively.

The $t\bar{t}$ background is modelled using MC@NLO and is normalized to the approximate NNLO cross section calculated using HATHOR [24]. The effect of the QCD scale uncertainty on the cross section is ${}^{+4}_{-9}\%$, while the effect of PDF and α_S uncertainties is ${}^{+7}_{-7}\%$. Both ALPGEN and MC@NLO are interfaced to HERWIG [25] for parton shower hadronization and to JIMMY for the underlying event simulation.

3.2 Signal Extraction

3.2.1 Object definitions

Electrons

Electrons in ATLAS are reconstructed using information from the inner tracking detector (ID) and the electromagnetic calorimeter (ECal): candidates are clusters of energy associated with ID tracks (track fit allows for Bremsstrahlung energy losses).

Background discrimination relies on the shower shape information available from the highly segmented calorimeter, high-threshold transition radiation

tracker (TRT) hits, as well as compatibility of the tracking and calorimeter information. This information is combined into a likelihood discriminant (in Run 1 it was only based on discriminating variables). Requirements on the hits in the silicon detectors, including a hit in the innermost layer of the detector, the IBL (or the next-to-innermost layer in case of masked modules), are added.

For Run 2, the impact parameter in the transverse plane and its significance ($|d0|$, and $|d0|/\sigma_{d0}$) have been added to the likelihood discriminant, improving the suppression of heavy-flavour background contributions. A *Loose* likelihood (LH) selection is applied, which maintains a high efficiency and sufficient background suppression (see Chapter 2) and the electron transverse energy (E_T) is computed from the cluster energy and the track direction at the interaction point.

Muons

Muons are reconstructed as tracks in the ID and the muon spectrometer (MS), and their identification is primarily based on the presence of a matching track or tag in the MS. The minimum muon transverse momentum requirement has been lowered from 6 GeV to $p_T > 5$ GeV from Run 1 to Run 2 measurements in order to increase the signal acceptance of about 7% in the 4μ final state. If the ID and MS feature full track information, a combined muon track is formed by a global refit using the hit information from both the ID and MS detectors (combined muons), otherwise the momentum is measured using the ID, and the partial MS track serves as identification (segment-tagged muons). The segment-tagged muons are limited in Run 2 to the centre of the barrel region ($|\eta| < 0.1$) which lacks MS geometrical coverage. Furthermore in this central region, an ID track with $p_T > 15$ GeV is identified as a muon if its calorimetric energy deposition is consistent with a minimum ionizing particle (MIP). The muon reconstruction and identification coverage is extended by using tracks reconstructed in the forward region ($2.5 < |\eta| < 2.7$) of the MS, which is outside the ID coverage (standalone muons). For standalone muons, the measurement of the impact parameter is improved by looking for possible hits in the part of the ID closest to the interaction point. The ID tracks associated with muons that are identified inside the ID acceptance are required to have a minimum number of associated hits in each of the ID subdetectors to ensure good track reconstruction. The muon candidates outside the ID acceptance that are reconstructed only in the MS are required to have hits in each of the three MS stations they traverse. At most one standalone or calorimeter-tagged muon is used per event.

Photons

Final State Radiation (FSR) photons can be identified in the calorimeter

and associated to the leptons thanks to the fact that the QED process of radiative photon production in Z boson decays is well modeled by simulation. The strategy to include FSR photons into the reconstruction of Z bosons consists of a search for collinear (for muons) and noncollinear FSR photons (for both muons and electrons) with only one FSR photon allowed per event.

Jets

Jets are reconstructed from clusters of calorimeter cells using the Anti- k_T algorithm ¹ with a distance parameter $R = 0.4$. The jets are calibrated using a dedicated scheme designed to adjust, on average, the energy measured in the calorimeter to that of the true jet energy. To reduce the number of jet candidates originated from pileup vertices, jets with $p_T < 60$ GeV within the ID acceptance ($|\eta| < 2.4$) have requirements applied to the fraction of tracks which come from the primary vertex.

Overlap removal

Different objects can be reconstructed from the same detector information, requiring an overlap ambiguity to be resolved. For an electron and a muon which share the same ID track, the muon is selected except for a calorimeter-tagged muon which does not have a MS track or segment-tag in which case the electron is selected. The reconstructed jets which overlap with electrons are removed.

3.2.2 Event selection

Events are required to have at least one vertex with two associated tracks with $p_T > 400$ MeV, and the primary vertex is chosen to be the reconstructed vertex with the largest Σp_T^2 . Four-lepton events are required to have the triggering lepton(s) correctly matched to one or two of the selected leptons; and are classified according to their final state: $4\mu, 2e2\mu, 2\mu2e, 4e$.

Candidates are formed by selecting two same-flavour, opposite-sign lepton pairs (a lepton quadruplet) in an event and a kinematic cut based selection is applied to the leptons.

In order to cope with the increase of the reducible background due to the lowering of the minimum muon p_T requirement (lowered from 6 to 5 GeV), the four leptons are required to be compatible with the same vertex:

- muons with p_T greater than 6 GeV or electrons with E_T greater than 7 GeV and be measured in the pseudo-rapidity range $|\eta| < 2.47$ ($|\eta| < 2.7$).

¹It is an algorithm for the clustering whose aim is to suppress the noise and pileup by keeping only cells with a significant energy deposit and their neighboring cells.

- The highest p_T lepton in the quadruplet must satisfy $p_T > 20$ GeV, and the second (third) lepton in p_T order must satisfy $p_T > 15$ GeV ($p_T > 10$ GeV).

A loose χ^2 selection has been applied in Run2 to require a common vertex for the leptons, corresponding to a signal efficiency of 99.5% for all decay channels.

Impact parameter requirements

Impact parameter requirements are applied to reject cosmic rays and to select leptons from the primary vertex:

- The impact parameter of each lepton along the beam axis (z_0) is required to be within 10 mm of the reconstructed primary vertex but this cut is not applied for muons in the forward region since as they are reconstructed as stand alone muons, they are not associated to an ID track.
- To reject cosmic rays, muons with an ID track are required to have a transverse impact parameter (d_0), defined as the impact parameter in the bending plane with respect to the primary vertex, of less than 1 mm (figure 3.2). These requirements on the impact parameter are important in order to distinguish from events that do not belong to the primary vertex (typically background events).
- The impact parameter significance, defined as the impact parameter divided by its uncertainty, $|d_0|/\sigma_{d_0}$, for all muons (electrons) is required to be lower than 3.5 (6.5). The electron impact parameter is affected by bremsstrahlung and thus it has a broader distribution.

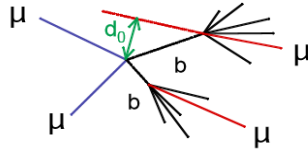


Figure 3.2: A $b\bar{b}$ background event in which the transverse impact parameter, that plays an important role in identifying reducible background events is shown.

Isolation requirements

Isolation requirements are used in order to select signal events and reject backgrounds:

- the $\Sigma p_T/p_T$ in a cone of radius ΔR around the track of the lepton less than the 10% of the lepton- p_T/E_T (figure 3.3). The leptons are required to be separated from each other by $\Delta R > 0.1$ if they are of the same flavour and $\Delta R > 0.2$ otherwise. The normalised track isolation discriminant is defined as the sum of the transverse momenta of tracks inside a cone of $\Delta R < 0.2$ around the lepton, excluding the lepton track, divided by the lepton E_T/p_T (e/μ). The calorimeter isolation normalised to the electron E_T cut is 0.3, while muons are required to have a normalised calorimetric isolation less than 0.3 (0.15 in case of muons without an ID track). For both the track- and calorimeter-based isolation any contributions arising from other leptons of the quadruplet are subtracted.

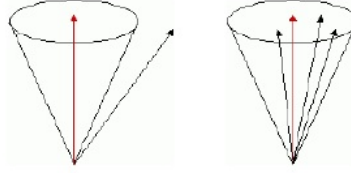


Figure 3.3: The isolation requirement on the lepton is done using the p_T/E_T in a cone around the track. On the left there is in red an isolated track, while on the right there is a non isolated track.

Quadruplet selection

Multiple quadruplets within a single event are possible: for four muons or electrons there are two ways to pair the masses, and for five or more leptons there are multiple ways to choose the leptons. Only quadruplets with the same-flavour and opposite-sign lepton pair closest to the Z boson mass are considered. The pair with the mass closest to the Z boson mass is referred to as the leading di-lepton and its invariant mass, m_{12} , is required to be between 50 and 106 GeV. The remaining same-flavour, opposite-sign lepton pair is the sub-leading di-lepton and its invariant mass, m_{34} , is required to be in the range $m_{min} < m_{34} < 115$ GeV, where m_{min} is 12 GeV for $m_{4\ell} < 140$ GeV and rises linearly to 50 GeV at $m_{4\ell} = 190$ GeV. It stays at 50 GeV for $m_{4\ell} > 190$ GeV. The Z boson corresponding to the leading (sub-leading) di-lepton pair is labelled Z_1 (Z_2).

All possible same-flavour opposite-charge di-lepton combinations in the quadruplet must satisfy $m_{4\ell} > 5$ GeV to remove events containing $J/\psi \rightarrow \ell\ell$. If two or more quadruplets satisfy the above selection, the one with the m_{34} value closest to the Z boson mass is selected.

The selection criteria that define the signal candidate events are summarized in Figure 3.4.

Leptons and Jets requirements	
ELECTRONS	
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7\text{GeV}$ and $ \eta < 2.47$	
MUONS	
Loose identification $ \eta < 2.7$	
Calo-tagged muons with $p_T > 15\text{GeV}$ and $ \eta < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5\text{GeV}$	
JETS	
anti- k_t jets with $p_T > 30\text{GeV}$, $ \eta < 4.5$ and passing pile-up jet rejection requirements	
Event Selection	
QUADRUPLET SELECTION	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10GeV Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: $50\text{GeV} < m_{12} < 106\text{GeV}$ Sub-leading dilepton mass requirement: $12 < m_{34} < 115\text{GeV}$ Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5\text{GeV}$ $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
ISOLATION	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T/p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$): $\Sigma E_T/E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/E_T < 0.20$
IMPACT PARAMETER SIGNIFICANCE	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $d_0/\sigma_{d_0} < 5$ For muons : $d_0/\sigma_{d_0} < 3$
VERTEX SELECTION	Require a common vertex for the leptons $\chi^2/\text{ndof} < 6$ for 4μ and < 9 for others.

Figure 3.4: Schematic summary of the selection criteria applied in order to select the four lepton candidates in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel.

FSR Correction

The effect on the reconstructed invariant mass due to photon emission from Final State Radiation (FSR) is modelled by the MC (Figure 3.5). All di-muon Z_1 candidates with $66 \text{ GeV} < m_{12} < 89 \text{ GeV}$ are corrected for FSR by including in the invariant mass any reconstructed photon with E_T above 1 GeV lying close ($\Delta R < 0.08$ to 0.15 depending on E_{gamma}^T) to one of the muon tracks, providing the corrected m_{12} satisfies $m_{12} < 106 \text{ GeV}$. This recovers 70% of the FSR photons within the selected fiducial region. About 85% of the corrected events have genuine FSR photons, with the remaining misidentified photons coming from pileup and muon ionization. The MC predicts that 4% of all $H \rightarrow ZZ^* \rightarrow 4\mu$ candidate events should have this correction applied. This correction is applied only on 4μ final state since electron are already corrected for Bremsstrahlung losses and muons have clear signatures in the apparatus which permit a better reconstruction of this process (Figure 3.6).

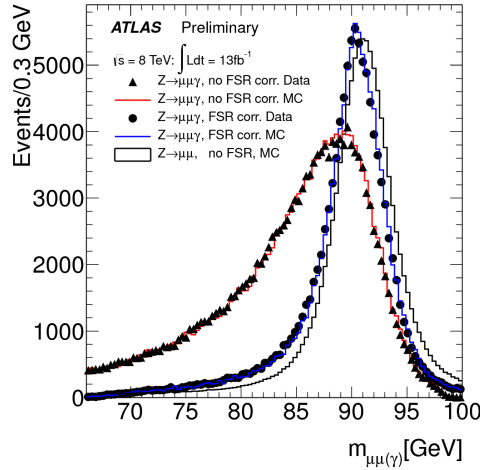


Figure 3.5: Mass distribution of $Z \rightarrow \mu^+ \mu^-$ events in data before FSR correction (triangles) and after FSR correction (bullets). The MC prediction is shown before correction (red histogram) and after correction (blue histogram).

Z-mass constraint

The Z line-shape and the experimental uncertainty in the di-lepton mass are accounted for in the Z-mass constraint, which is a kinematic fit that includes physical laws in minimization problems. The 4ℓ invariant mass resolution has been improved by applying the Z-mass constraint to the leading di-lepton pair. Constraining the mass value would guarantee that there are no systematics effects on the mass measurements. Figure 3.7 presents the $m_{4\mu}$

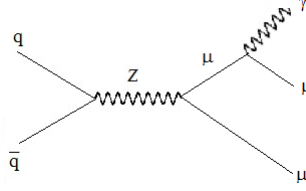


Figure 3.6: Feynman diagram showing the Final State Radiation (FSR) photon correction in a $q\bar{q} \rightarrow Z \rightarrow \mu^+\mu^-\gamma$ process.

distributions before and after applying the Z-mass constraint of a simulated signal sample with $m_H = 125$ GeV, at $\sqrt{s} = 8$ TeV. The effects of the FSR

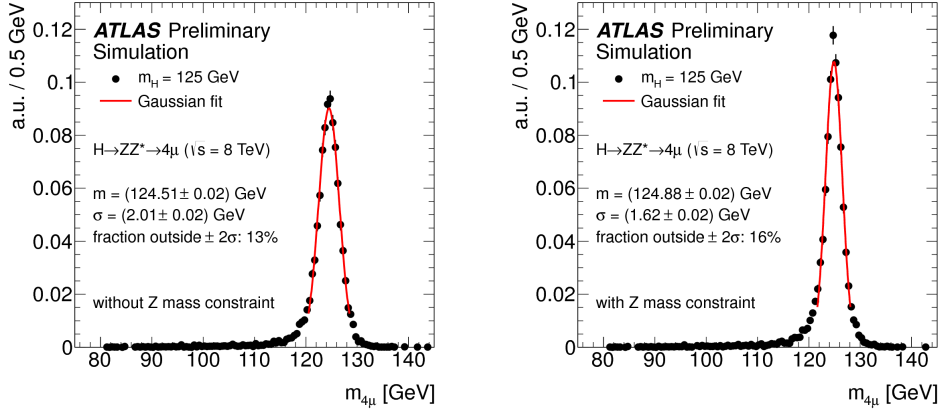


Figure 3.7: (left) The invariant mass distribution of the 4 muon system ($m_{4\mu}$) without applying the Z-mass constraint of a simulated signal sample with $m_H = 125$ GeV, at $\sqrt{s} = 8$ TeV. (right) The invariant mass distribution of the 4 muon system ($m_{4\mu}$) when applying the Z-mass constraint of a simulated signal sample with $m_H = 125$ GeV, at $\sqrt{s} = 8$ TeV [27].

correction, of the Mass Constraint on m_{Z_1} , and the simultaneous application of the two are shown in Figure 3.8 in comparison to the case in which no corrections are applied. After the FSR correction, the lepton four-momenta of the leading dilepton are recomputed by means of a Z-mass-constrained kinematic fit. The fit uses a Breit-Wigner Z line shape and a single Gaussian per lepton to model the momentum response function with the Gaussian σ set to the expected resolution for each lepton.

The Z-mass constraint improves the $m_{4\ell}$ resolution by about 15%.

Events satisfying the above criteria are considered candidate signal events defining a signal region independent of the value of $m_{4\ell}$. The Higgs boson mass resolution is dependent on the final state and corresponds to 1.6 GeV, 1.7 GeV, 2.1 GeV and 2.4 GeV for $4\mu, 2e2\mu, 2\mu2e$ and $4e$ at $m_H = 125$ GeV,

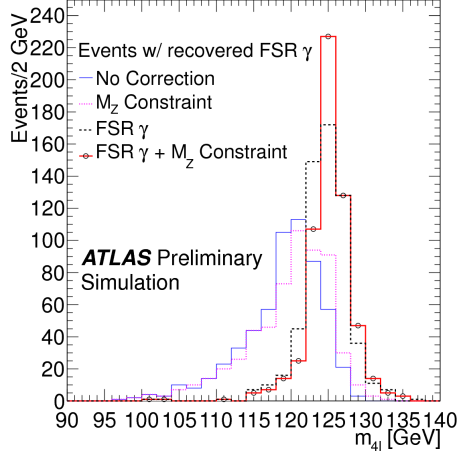


Figure 3.8: Mass distribution of simulated $H \rightarrow ZZ^* \rightarrow 4\ell$ events with mass $m_H = 125$ GeV in which an FSR photon has been identified. The mass distribution before any correction is shown (blue solid histogram) and after the FSR photon is recovered (purple dotted histogram). The effect of applying the constraint on the invariant mass of the leading di-lepton pair for these two cases is also shown (black dashed and red solid histograms, respectively).

respectively.

3.3 Background estimates

3.3.1 Irreducible background

The contribution of the irreducible ZZ^* background is estimated using MC simulation normalized to the theoretical cross section (which is known with an uncertainty of $\sim 10\%$) and its consistency with data is checked by looking at Control Regions (CR) of the four leptons invariant mass choosing a region which is orthogonal to the signal one but either more populated, either kinematically similar to the signal one.

3.3.2 Reducible background

The production cross section for the reducible background processes at $\sqrt{s} = 8$ TeV are:

- $t\bar{t}$: $\sigma_{(pp \rightarrow t\bar{t})} \times BR_{(t\bar{t} \rightarrow WbWb \rightarrow X+4\ell)} = 240 \times 10^3 \text{ fb} \times 10^{-4} \sim 24 \text{ fb}$ for $pp \rightarrow t\bar{t}$ with a final state characterized by 4 leptons coming either from the Ws decays (10% in lepton-neutrino) or from the b-jets $\sim 10\%$ of the

times (figure 3.9). The effective cross section ², therefore the analysis shows a rejection power of 10^3 :

$$R = \frac{\sigma_{(pp \rightarrow t\bar{t})} \times BR_{(t\bar{t} \rightarrow WbWb \rightarrow X+4\ell)}}{\sigma_{eff_{t\bar{t}}}} = \frac{24 \text{ fb}}{10^{-2} \text{ fb}} = 2.4 \times 10^3 \quad (3.1)$$

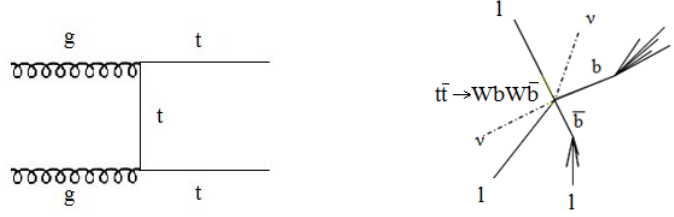


Figure 3.9: (left) Feynman diagram of a gluon initiated $t\bar{t}$ event production. (right) The 4-lepton final state coming from the $t\bar{t}$ decay.

- $Z + jets$: $\sigma_{(pp \rightarrow Zb\bar{b})} \times BR_{(b\bar{b} \rightarrow X+2l)} \times BR_{(Z \rightarrow 2l)} = 4 \times 10^3 \text{ fb} \times 3 \times 10^{-4} \sim 1.2 \text{ fb}$ for $pp \rightarrow Zb\bar{b}$ with a final state characterized by 2 leptons coming from the Z boson decay (3% in di-lepton) and the other two from the b -jets whose 10% is composed by leptons (figure 3.10). The effective cross section of the events passing the cut-based selection is $\sigma_{eff_{Zb\bar{b}}} \sim 5 \times 10^{-2} \text{ fb}$, therefore the analysis shows a rejection power of 10^2 :

$$R = \frac{\sigma_{(pp \rightarrow Zb\bar{b})} \times BR_{(b\bar{b} \rightarrow X+2l)} \times BR_{(Z \rightarrow 2l)}}{\sigma_{eff_{Zb\bar{b}}}} = \frac{1.2 \text{ fb}}{5 \times 10^{-2} \text{ fb}} = 2.4 \times 10^2 \quad (3.2)$$

The cross sections of these reducible background processes are orders of magnitude greater than that for the $H \rightarrow ZZ^* \rightarrow 4\ell$ and therefore, a very high rejection power is required on those. Theory uncertainties on the reducible background cross sections are not negligible, and even going from the LO contribution to the NLO contribution a k factor of 1.6 needs to be applied ³.

This is the reason why data-driven methods are used to better estimate the reducible background contribution in the signal region.

Control Regions (CR), in which the reducible background contributions are enhanced and the signal is strongly suppressed, are therefore established in order to have a better background determination and control.

² $\sigma_{eff} = \sigma\epsilon$ of the events passing the cut-based selection is $\sigma_{eff_{t\bar{t}}} \sim 10^{-2} \text{ fb}$, where ϵ is the selection efficiency.

³The scale factor $k = \frac{\sigma_{NLO}}{\sigma_{LO}}$; the k factor is an extra factor that has to be applied to account for NLO correction.

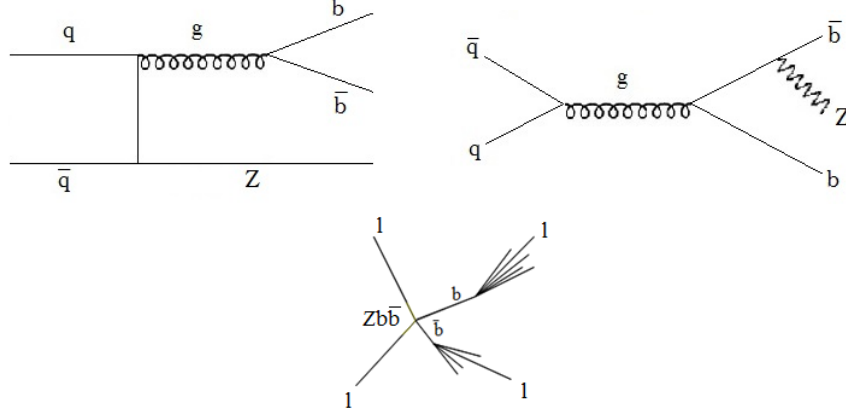


Figure 3.10: (up) Feynman diagrams of a quark initiated $Zb\bar{b}$ event. (down) The 4-lepton final state coming from the $Zb\bar{b}$ decay.

To build a CR the requirements on the leptons have to be changed in order to select events of reducible background instead of signal events.

The isolation or impact parameter requirements play a fundamental role in defining a CR, since leptons coming from b -quark jets are not isolated and do not come from the primary vertex.

From the comparison of the data observed with respect to the number of events expected from MC simulation, one can test if the shape of relevant distributions and the normalizations of the reducible backgrounds from MC are in agreement with data. The *scale factor* (sf) to the MC expectation for each background component is defined as a measurement of data-MC agreement; it is a normalization factor used to rescale the MC and to correct the normalization obtained from data.

The transfer factors needed to extrapolate the background yields from the control regions (defined below) to the signal region are obtained from the MC simulation.

Since the background composition depends on the flavour of the sub-leading lepton pair, different approaches are taken for the $ll + \mu\mu$ and the $ll + ee$ final states.

The $ll + \mu\mu$ reducible background

The $ll + \mu\mu$ reducible background arises from $Z + jets$ and $t\bar{t}$, where saying $Z + jets$ include both the heavy quark $Zb\bar{b}$ contribution and the small $Z + light - jets$ component.

To enhance the $Zb\bar{b}$ and $t\bar{t}$ component, CRs can be built inverting the isolation and impact parameter requirements on the sub-leading leptons (Figure 3.11), but such a CR suffer of low statistics. A different CR is then con-

structed by inverting the impact parameter requirement and relaxing the isolation cuts on the sub-leading pair in order to increase the statistics. Those requirements both contribute to enhance the $\bar{t}t$ and $Z\bar{b}b$ components (which can be therefore estimated simultaneously), and to remove a large fraction of ZZ^* events.

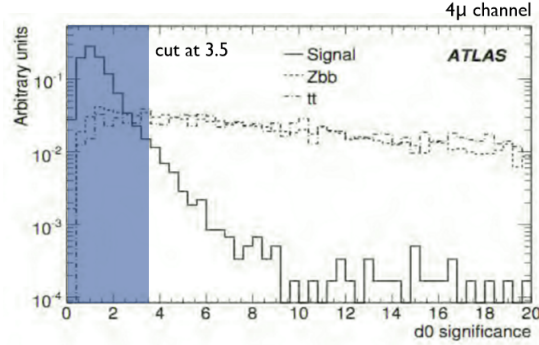


Figure 3.11: Significance of the impact parameter for the signal and the main reducible background processes.

The $\ell\ell + ee$ reducible background

A sample of reconstruction-level objects identified as electron candidates will contain true isolated electrons, electrons from heavy flavour semi-leptonic decays (Q), electrons from photon conversions (γ) or light jets mis-reconstructed as electrons denoted as fake electrons (f). Those different sources of background electrons are separated into reconstruction categories which are electron-like (E), and fake-like (F), using appropriate discriminating variables such as: fraction of high threshold hits in the TRT (RTRT), the fraction of energy in the first layer of the electromagnetic calorimeter (f1), and the lateral containment of the cluster in the azimuthal direction in the second layer of the electromagnetic calorimeter ($R\phi$).

The $\ell\ell + ee$ background Control Region is then formed by relaxing the electron selection criteria for the electrons of the sub-leading pair; the events in the signal region being a subset of the events present in this Control Region. Estimates of the relative composition of the Control Region in terms of its isolated electron, Q , γ , and f components are performed using the classification into different categories and the efficiency needed to extrapolate the background yield of each category from the Control Region to the signal region is obtained from MC, and cross-checked with data.

Additionally, the $\ell\ell + ee$ background is also estimated from a Control Region which is well separated from the signal region, defined by inverted isolation and impact parameter significance selections, and has been classified

into the reconstruction categories and also by performing the full analysis but selecting same-sign pairs for the sub-leading di-electrons to compare the results.

3.4 Reconstructed invariant masses of the events passing the selection

In Figures 3.12 and 3.13 the invariant mass of the 4ℓ system is presented inclusively and in each sub-decay channels both for the Run 1 and Run 2 data sets. Figures 3.14 and 3.15 shows the signal and background yields in the $H \rightarrow ZZ^* \rightarrow 4\ell$ Run 1 and Run 2 analysis.

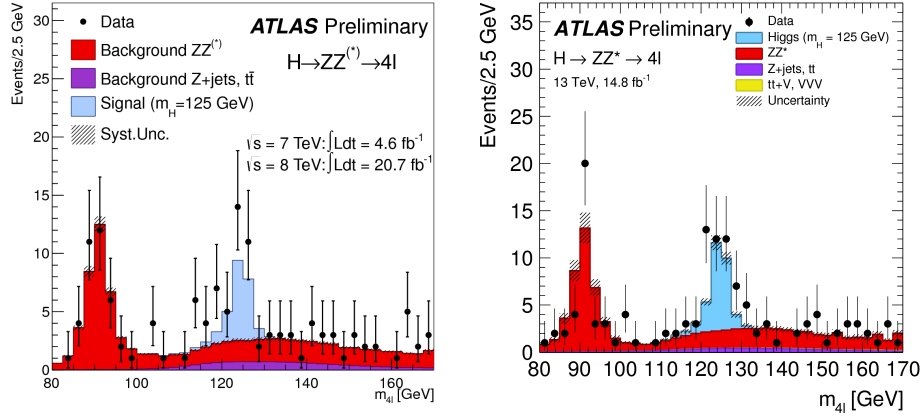


Figure 3.12: The distributions of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates compared to the background expectation for the combined $\sqrt{s} = 7 - 8$ TeV (left) and $\sqrt{s} = 13$ TeV (right) data sets. The signal expectation for the $m_H = 125$ GeV hypothesis is also shown.

3. The $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e, \mu$) decay channel reconstruction and event selection

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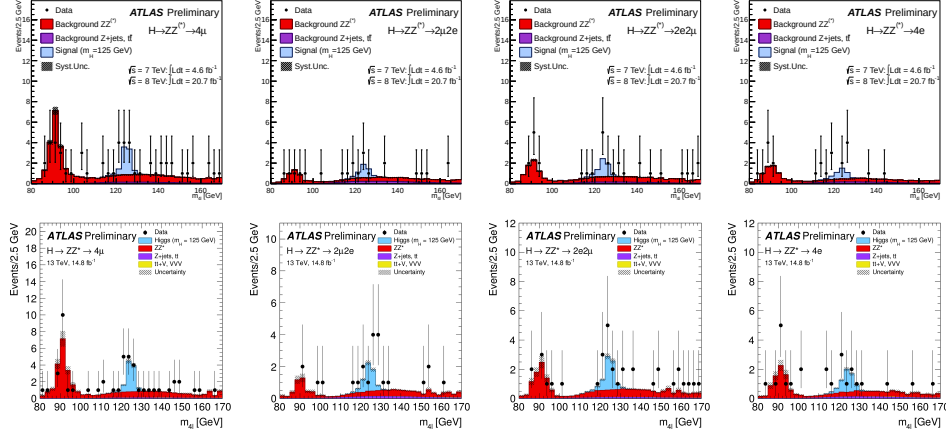


Figure 3.13: The distributions of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates for the combined $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV data sets (top) and $\sqrt{s} = 13$ TeV data set (bottom) the for the various sub-channels compared to the background expectation. The signal expectation for the $m_H = 125$ GeV hypothesis is also shown.

	total signal full mass range	signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	S/B	expected	observed
$\sqrt{s} = 8$ TeV							
4μ	5.8 ± 0.7	5.3 ± 0.7	2.3 ± 0.1	0.50 ± 0.13	1.9	8.1 ± 0.9	11
$2\mu 2e$	3.0 ± 0.4	2.6 ± 0.4	1.2 ± 0.1	1.01 ± 0.21	1.2	4.8 ± 0.7	4
$2e 2\mu$	4.0 ± 0.5	3.4 ± 0.4	1.7 ± 0.1	0.51 ± 0.16	1.5	5.6 ± 0.7	6
$4e$	2.9 ± 0.4	2.3 ± 0.3	1.0 ± 0.1	0.62 ± 0.16	1.4	3.9 ± 0.6	6
total	15.7 ± 2.0	13.7 ± 1.8	6.2 ± 0.4	2.62 ± 0.34	1.6	22.5 ± 2.9	27
$\sqrt{s} = 7$ TeV							
4μ	1.0 ± 0.1	0.97 ± 0.13	0.49 ± 0.02	0.05 ± 0.02	1.8	1.5 ± 0.2	2
$2\mu 2e$	0.4 ± 0.1	0.39 ± 0.05	0.21 ± 0.02	0.55 ± 0.12	0.5	1.2 ± 0.1	1
$2e 2\mu$	0.7 ± 0.1	0.57 ± 0.08	0.33 ± 0.02	0.04 ± 0.01	1.5	0.9 ± 0.1	2
$4e$	0.4 ± 0.1	0.29 ± 0.04	0.15 ± 0.01	0.49 ± 0.12	0.5	0.9 ± 0.1	0
total	2.5 ± 0.4	2.2 ± 0.3	1.17 ± 0.07	1.12 ± 0.17	1.0	4.5 ± 0.5	5
$\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV							
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e 2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

Figure 3.14: The number of expected and observed events for the four-lepton final states for the Run 1 dataset are quoted.

Final State	Signal full mass range	Signal	ZZ^*	$Z + \text{jets}, t\bar{t}$ ttV, VVV, WZ	S/B	Expected	Observed
4μ	8.8 ± 0.6	8.2 ± 0.6	3.11 ± 0.30	0.31 ± 0.04	2.4	11.6 ± 0.7	16
$2e2\mu$	6.1 ± 0.4	5.5 ± 0.4	2.19 ± 0.21	0.30 ± 0.04	2.2	8.0 ± 0.4	12
$2\mu 2e$	4.8 ± 0.4	4.4 ± 0.4	1.39 ± 0.16	0.47 ± 0.05	2.3	6.2 ± 0.4	10
$4e$	4.8 ± 0.5	4.2 ± 0.4	1.46 ± 0.18	0.46 ± 0.05	2.2	6.1 ± 0.4	6
Total	24.5 ± 1.8	22.3 ± 1.6	8.2 ± 0.8	1.54 ± 0.18	2.3	32.0 ± 1.8	44

Figure 3.15: The number of expected and observed events for the four-lepton final states for $14.8 fb^{-1}$ at $\sqrt{s} = 13$ TeV.

Chapter 4

Fiducial inclusive and differential cross section measurements in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with the Run1 dataset

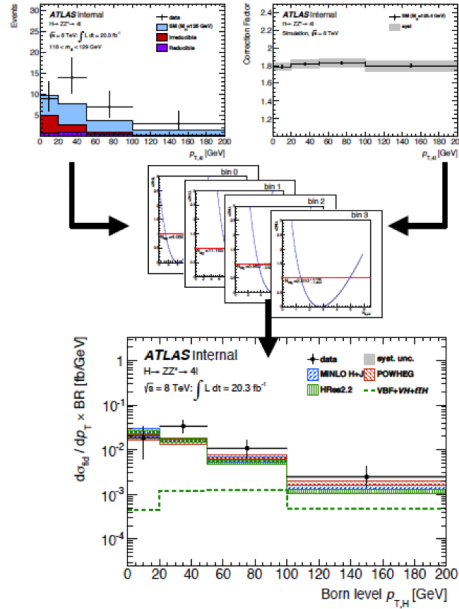


Figure 4.1: Schematic view of the Differential Cross section measurement performed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel with 20.3 fb^{-1} of data recorded at $\sqrt{s} = 8 \text{ TeV}$.

The measurements of the differential cross sections (XSs) of the Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel has a crucial role in studying possible deviations from the SM due to the fact that the differential-XSs can be expressed in terms of variables sensitive to possible Beyond the Standard Model (BSM) effects.

Data recorded at $\sqrt{s} = 8$ TeV corresponding to 20.3 fb^{-1} have been used for this analysis.

A number of variables which describe the event kinematics and properties of the Higgs boson candidate events are measured.

The $H \rightarrow 4\ell$ decay channel is particularly interesting because the full Higgs kinematic information is accessible through the reconstruction of all of the Higgs decay products.

The kinematics of the Higgs particle in a pp collision can be described by the transverse momentum $p_{T,H}$, the azimuthal direction Φ , and the rapidity y_H .

The decay to four leptons is described by the invariant mass of the leading lepton pair m_{12} , the invariant mass of the sub-leading lepton pair m_{34} , and five decay angles ($\Phi, \Phi_1, \theta^*, \theta_1, \theta_2$) between the leptons as shown in Fig. 4.2. The dilepton masses and decay angles are sensitive to the properties of the Higgs itself and can also test the presence of other particles being produced in association with the Higgs boson. Among those variables, the Higgs boson differential transverse momentum cross section is of particular interest as the theoretical cross section predictions have been studied extensively in literature (see e.g. [19], [20] and [21]). The treatment of the top and bottom quark masses in the calculation of the ggH production mode cross section can lead to order 10% differences in the differential transverse momentum cross section [22], however, it should be noticed that the statistical power of the current data set does not allow the analysis to reach the level of statistical precision required to verify these calculations.

4.1 The measurement at a glance

The total cross-section of a process σ_{tot} can be calculated as:

$$\sigma_{tot} \cdot BR = \frac{N_{sig}}{\epsilon_{tot} \cdot \mathcal{L}_{int}}. \quad (4.1)$$

where BR is the branching ratio of the decay mode, N_{sig} is the number of observed signal events ($N_{sig} = N_{obs} - N_{bkg}$), $\mathcal{L}_{int}$ the integrated luminosity, and ϵ_{tot} is the efficiency for detecting the signal process, accounting for trigger, reconstruction and identification efficiencies.

The total efficiency is a very model-dependent parameter, since it takes into account events which are outside the detector acceptance; meaning that the total efficiency extrapolate the observed measurements to regions of phase

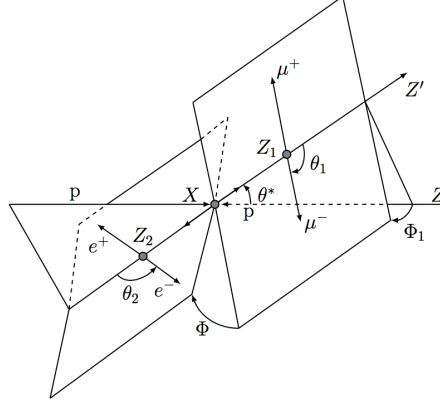


Figure 4.2: Diagram of decay angles for the $H \rightarrow 4\ell$ decay.

space in which the detector has no sensitivity.

In order to remove this model-dependence, the total efficiency can be split into two terms:

$$\epsilon_{tot} = A_{fid} \cdot \epsilon_{fid} \quad (4.2)$$

where A_{fid} is the fiducial acceptance, the fraction of events that fall within the fiducial volume of the detector and ϵ_{fid} is the fiducial efficiency, the signal efficiency within the fiducial volume of the detector.

Therefore a fiducial cross section σ_{fid} can be defined as:

$$\sigma_{fid} \cdot BR = \frac{N_{sig}}{\epsilon_{fid} \cdot \mathcal{L}_{int}} \quad (4.3)$$

The inclusive fiducial cross section measurement has been performed using two methods: a simple cut and count measurement within a mass window around the signal resonance at ~ 125 GeV and a more precise measurement based on a fit of the invariant mass distribution of the 4ℓ system.

Furthermore, several differential fiducial cross section measurements are also reported for variables which show a peculiar sensitivity to the Higgs boson properties. Six variables that describe the Higgs kinematics or are sensitive to the details of the Higgs boson production and decay have been chosen in order to test the shapes of the observables. All predictions are normalized to the best estimate of the cross sections for a SM Higgs boson with $m_H = 125.4$ GeV as from the combined ATLAS measurement [42].

The method used is based on a simple event counting in a 4-leptons mass window chosen to minimize the error on the measured signal yield (discussed in Section 4.3.1). Within this mass window, for each bin of the differential variables, the number of signal events is determined by subtracting the expected background from the data.

A schematic view of the measurement strategy is reported in Figures 4.1 and 4.3. The signal is then unfolded to the 4-leptons particle level using tech-

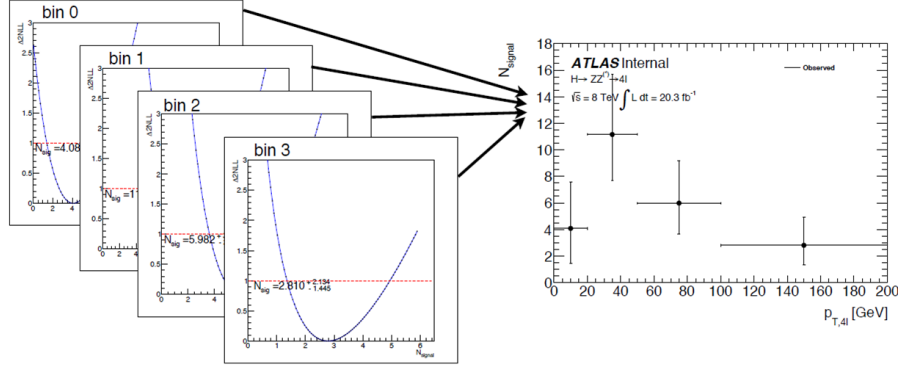


Figure 4.3: Schematic view of the Differential Cross section measurement performed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel with 20.3 fb^{-1} of data recorded at $\sqrt{s} = 8 \text{ TeV}$.

niques based on the correction factors method, described in Section 4.3.6. Correction Factors ($CFs = 1/\epsilon_{fid}$), derived from simulation, are defined to take into account the detector efficiency and the bin-by-bin migrations caused by the detector response.

Systematic uncertainties on the expected backgrounds and on the signal correction factors have been already described in Section 4.4.

The derived differential cross-sections are shown in Section 4.6.2 and compared to a number of theory predictions, namely Powheg interfaced to Pythia8, HRes2.0 for the kinematic variables and MinLo+1H (also interfaced to Pythia8) for the jet variables.

As noted above, Powheg calculates the cross section at NLO, Minlo is accurate to NLO for Higgs+1 jet events, while HRes2 provides NNLO calculations of ggF with a soft-gluon resummation at small transverse momenta up to NNLL. Additional contributions from VBF (simulated with Powheg+Pythia), VH and $t\bar{t}H$ (Pythia) processes are added to the estimate.

4.2 Fiducial Region definition

The fiducial region cuts (made at truth level) are chosen to mimic the reconstruction level selection in order to minimize model-dependent acceptance effects on the measured fiducial cross section. At the same time, it is important to make the fiducial region cuts easily reproducible with different event generators/matrix element calculations.

The fiducial region is then defined as follows:

- **Lepton acceptance:**

$$p_T > 7 \text{ (6) GeV for electrons (muons)}$$

$$|\eta| < 2.47 \text{ (2.7) for electrons (muons)}$$

- **Leading lepton kinematics:**

$$p_T > 20, 15, 10 \text{ GeV}$$

- **Mass-pair cuts:**

$$50 < m_{12} < 106 \text{ GeV}; 12 < m_{34} < 115 \text{ GeV}$$

- **Lepton separation:**

$$\Delta R(\ell_i, \ell_j) > 0.1(0.2) \text{ for same (opposite) flavor leptons}$$

- J/ψ **veto:**

$$M(\ell_i, \ell_j) > 5 \text{ GeV for same flavor opposite sign lepton pairs}$$

- **Mass Window:**

$$118 < m_{4\ell} < 129 \text{ GeV}$$

For m_{12} , m_{34} , and $m_{4\ell}$ cuts, the leptons are paired using the same method as the reconstruction selection, allowing the possibility of mispairing the leptons¹. This also includes selection of leptons which are not direct decay products of the Higgs boson that can be selected when the Higgs is produced in association with a vector boson which decays leptonically.

The signal samples used to derive the correction factors include $H \rightarrow 2\tau 2\ell$ and $H \rightarrow 4\tau$ decays, which contribute $\sim 0.5\%$ of the reconstructed signal yield due to leptonic τ decays but, since many theory predictions only consider direct $H \rightarrow 4\ell$ decays, therefore, events containing $Z \rightarrow \tau\tau$ events are explicitly removed from the fiducial region in order to facilitate easier comparisons with theory predictions: which is equivalent to treating it as a background.

Reconstructed object definitions and event selection

An overview of the reconstructed object definitions is presented, as already discussed in Chapter 3.

- **Electrons:**

- Reconstruction: ID tracks pointing to an EM calorimeter cluster.

¹the mispairing is what emerges when the two Z bosons are reconstructed from two pair of leptons which does not match the truth ones and are mixed among them, i.e. "mispaired"

- Identification: MVA likelihood based on shower shapes in the EM calorimeter, properties of the track in the ID, and matching between tracks and clusters (*Loose* operating point).
- Kinematic cuts: $E_T > 7$ GeV, $|\eta| < 2.47$
- **Muons:**
 - Reconstruction: Standalone (SA), Combined (CB), Segment Tagged (ST), Calorimeter Tagged (CT)
 - Hit requirements: see Chapter 3
 - Kinematic cuts: $p_T > 6$ GeV, $|\eta| < 2.7$
- **Jets:**
 - Reconstruction: From topological clusters using an anti- k_T algorithm [45] with the distance parameter $R = 0.4$
 - Jet cleaning: Required to pass “looser” quality cuts for ATLAS jets
 - Jet vertex fraction $|JVF| > 0.25$ if $|\eta| < 2.4$ and $p_T < 50$ GeV
 - Overlap removal: Remove jet if $\Delta R(jet, electron) < 0.2$
 - Kinematic cuts: $p_T > 30$ GeV, $|\eta| < 4.4$
- **Higgs candidate:** The Higgs candidate is composed of two pairs of same flavor opposite sign leptons. For each channel (4μ , $4e$, $2\mu 2e$, $2e 2\mu$), the leading pair is defined as the SFOS lepton pair with invariant mass closest to the PDG Z mass and the subleading pair is defined as the remaining SFOS lepton pair with invariant mass closest to the PDG Z mass. In case of more than one quadruplet formed, preference is given to the channels with higher resolution: 4μ , $2e 2\mu$, $2\mu 2e$, $4e$.

Truth object definitions

A selection of truth level objects is required in order to define the detector fiducial acceptance and determine the unfolding correction factors (defined in Section 4.3.6) to quote fiducial cross sections. At truth level, there are three options for the leptons definition:

- Bare leptons are the leptons after QED radiation;
- Born leptons are the leptons prior to QED FSR radiation;
- Dressed leptons collect photons around charged leptons within a certain cone.

The following criteria are then applied to truth physics objects:

- **Electrons:** $p_T > 7$ GeV, $|\eta| < 2.47$, as determined by the inner detector acceptance. Only Born electrons from Z and W decays are considered.
- **Muons:** $p_T > 6$ GeV, $|\eta| < 2.7$, as determined by the detector acceptance. Only Born muons from Z and W decays are considered.
- **Jets:** Particle-level jets are reconstructed from all stable particles except muons and neutrinos using the anti- k_t algorithm [45] with distance parameter $R = 0.4$. Each jet is required to have $p_T > 30$ GeV and $|y| < 4.4$ and must not be within $\Delta R < 0.2$ of any truth electron as selected above.
- **Higgs candidate:** The Higgs candidate is composed of two pairs of same flavor opposite sign (SFOS) truth leptons. The pairing is carried out the following way: the leading pair is defined as the SFOS lepton pair with invariant mass closest to the PDG Z mass and the subleading pair is defined as the remaining SFOS lepton pair with invariant mass closest to the PDG Z mass. Note that this is slightly different from the reconstruction, as no preference is given to higher resolution channel, in order to keep the selection as simple as possible. The difference is negligible. For the unfolded Higgs kinematic variables, p_T and y , the truth Higgs candidate is used.

Higgs boson event selection

Table 4.1 summarizes the $H \rightarrow 4\ell$ event selection as described in Chapter 3. Given the limited statistics, no categories in production modes are performed.

4.3 Signal Extraction

A profile likelihood² fit of the $m_{4\ell}$ distribution can be performed to extract the signal, but this would have required for the differential analysis, derivation of signal and background $m_{4\ell}$ templates in each bin of the variables of interest. Given the limited statistical significance expected in this measurement with $20.3 fb^{-1}$ at $\sqrt{s} = 8$ TeV, a simpler counting method in a selected $m_{4\ell}$ window has been chosen for the differential cross section measurement, however, concerning the inclusive cross section, the extraction of the signal yield has been performed in both ways:

²Profile likelihood attempts to stick to the original data distribution and likelihood function, but eliminates the nuisance parameters by maximization. The profile likelihood function $\hat{L}(\psi)$ for ψ is defined as $\hat{L}(\psi) = \sup_{\lambda} L(\psi, \lambda) = L(\psi, \hat{\lambda}(\psi))$, where ψ is the parameter of interest and $\hat{\lambda}(\psi)$ is the maximum likelihood estimation of λ when ψ is considered fixed.

The profile likelihood ratio test, in this sense, is the ratio of profile likelihoods built to test an hypothesis against the alternatives [43].

Table 4.1: Summary of the event selection requirements. The two lepton pairs are denoted as m_{12} and m_{34} . ($m_{threshold}$ varies with the four-lepton invariant mass $m_{4\ell}$; the value of $m_{threshold}$ is 12 GeV for $m_{4\ell} < 140$ GeV, rises linearly to 50 GeV with $m_{4\ell}$ in the interval $140 \leq m_{4\ell} \leq 190$ GeV and stays at 50 GeV for $m_{4\ell} > 190$ GeV.)

Event Pre-selection	
Electrons	
LOOSE LH quality electrons with $E_T > 7$ GeV and $ \eta < 2.47$	
Muons	
combined or segment-tagged muons with $p_T > 6$ GeV and $ \eta < 2.7$	
Maximum one calo-tagged or standalone muon	
calo-tagged muons with $p_T > 15$ GeV and $ \eta < 0.1$	
SA muons with $p_T > 6$ GeV, $2.5 < \eta < 2.7$ and $\Delta R > 0.2$ from closest ST	
Event Selection	
Kinematic Selection	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet 20, 15, 10 GeV Select best quadruplet to be the one with the leading dilepton mass being the one closer to the Z mass and the second mass closer to the Z one, to be the subleading one. Leading di-lepton mass requirement $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ Sub-leading di-lepton mass requirement $m_{threshold} < m_{34} < 115 \text{ GeV}$ Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5 \text{ GeV}$ and $\Delta R(\ell, \ell') > 0.10(0.20)$ for all same (different) flavour leptons in the quadruplet.
Isolation	Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T/p_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/E_T < 0.20$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/E_T < 0.30$ Stand-Alone muons calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/E_T < 0.15$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $d_0/\sigma_{d_0} < 6.5$ For muons : $d_0/\sigma_{d_0} < 3.5$

- the **counting method**: performed by subtracting the predicted number of background events from the number of observed events within a mass window ($m_{4\ell}$) around the signal peak (used also for the differential cross-section measurements);
- the **fit method**: performed on the $m_{4\ell}$ distribution in the region $[110, 140]$ GeV.

4.3.1 Mass Window Optimization

A window in $m_{4\ell}$ (the four-lepton mass after FSR correction and Z mass constraint) is chosen in order to maximize the significance around the signal peak.

To choose the window, an optimization procedure has been implemented using the inclusive signal (S) and background (B) yields and measuring:

- $S/\sqrt{S+B}$: the statistical significance
- $S/\sqrt{B}$: the significance vs the null hypothesis
- Z_0 , a more general formula for $S/\sqrt{B}$ applicable in a low statistical regime:

$$Z_0 = \sqrt{2((S+B) \cdot \ln(1+S/B) - S)} \quad (4.4)$$

each studied by simultaneously varying the lower and upper $m_{4\ell}$ cuts over the range $[110, 140]$ GeV. The final mass window is chosen using $S/\sqrt{S+B}$ because this will minimize the cross-section uncertainty, which will be dominated by the statistical uncertainty.

The results of this procedure can be seen in Figure 4.4 (left) for the signal sample with $M_H = 125$ GeV, together with the studies on the optimal window for Higgs boson masses from 123 GeV to 127 GeV (right) in order to understand the impact of the Higgs boson mass on the choice of mass window; the results are also reported in Table 4.2 and show that the optimal mass window directly shifts with the Higgs boson mass.

It can be notice that the significance changes more rapidly with the lower cut than the upper cut due to the longer tail on the low mass side of the signal peak. The ATLAS mass measurement of the Higgs boson in the $H \rightarrow 4\ell$ decay channel with $\sim 25fb^{-1}$ at $\sqrt{s} = 7/8$ TeV [42] measured the best fit mass to be 124.5 ± 0.5 GeV, therefore, given the current uncertainty in the Higgs mass, the mass scenarios from $m_H = 124$ to $m_H = 126$ GeV are considered in defining a window of $[118, 129]$ GeV, chosen by combining the ranges recommended by $S/\sqrt{S+B}$ for these masses.

4.3.2 Fiducial Studies

In this section, several fiducial quantities have been studied in order to validate the fiducial region definition and to understand the model-dependence

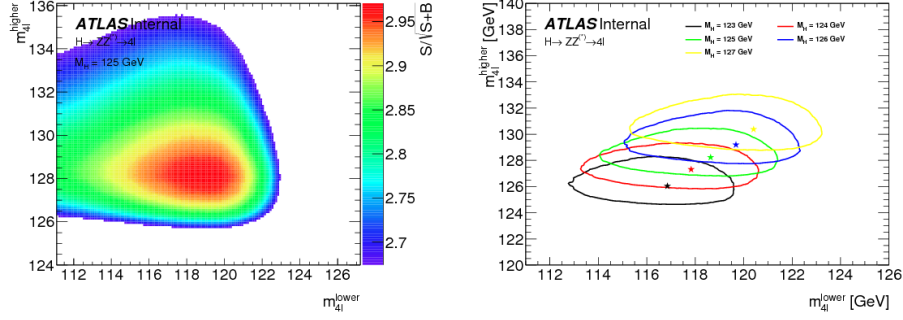


Figure 4.4: (left) $S/\sqrt{S+B}$ as a function of lower and upper $m_{4\ell}$ cuts for the mass window optimization for a 125 GeV sample. (right) Optimal mass window cuts as determined by $S/\sqrt{S+B}$ for various Higgs mass scenarios from 123 to 127 GeV. The stars indicate the cuts which maximize the given metric and the contours indicate where the metric decreases to 97.5% of its maximum value for a given Higgs mass.

M_H [GeV]	$S/\sqrt{B}$	Z_0	$S/\sqrt{S+B}$
123	[119.7, 124.9]	[118.9, 125.2]	[116.9, 126.0]
124	[120.5, 126.0]	[119.9, 126.5]	[117.8, 127.3]
125	[121.4, 127.1]	[120.7, 127.5]	[118.6, 128.2]
126	[122.5, 128.1]	[121.5, 128.4]	[119.7, 129.2]
127	[123.5, 128.8]	[122.5, 129.4]	[120.4, 130.4]

Table 4.2: Optimal mass window cuts for M_H from 123 GeV to 127 GeV.

of the inclusive measurement.

In particular, quantities such as the fiducial acceptance, the fiducial efficiency, the mispairing fraction and the fiducial leakage have been studied as a function of the Higgs mass, production mode, and decay channel in addition to several models with non-SM spin/ $\mathcal{CP}$ properties.

Fiducial Acceptance

The fiducial acceptance is defined as the number of fiducial events divided by the total number of generated events:

$$A_{fid} = N_{fid}/N_{gen} \quad (4.5)$$

Given an appropriate fiducial region definition, the acceptance describes the fraction of events which could possibly be reconstructed in the detector.

Figure 4.5 shows the fiducial acceptance as a function of m_H for all Higgs production modes: the fiducial acceptance is within 10% for all Higgs production modes with the exception of ttH when no mass window cut is applied ($Z \rightarrow \tau\tau$ decays are included in this inclusive definition of the acceptance). This is due to the fact that the ttH production mode has a larger lepton multiplicity which results in a combinatorially increasing number of possible pairings, i.e. higher efficiency for the m_{12} and m_{34} requirements due to mispairing, resulting in a larger fiducial acceptance.

After applying the mass window cut, the mispairing fraction greatly decreases in ttH and the fiducial acceptance is comparable to the other production modes (Figure 4.5); this reflects in a less model dependency on the production modes. The fiducial acceptance has been also studied for each

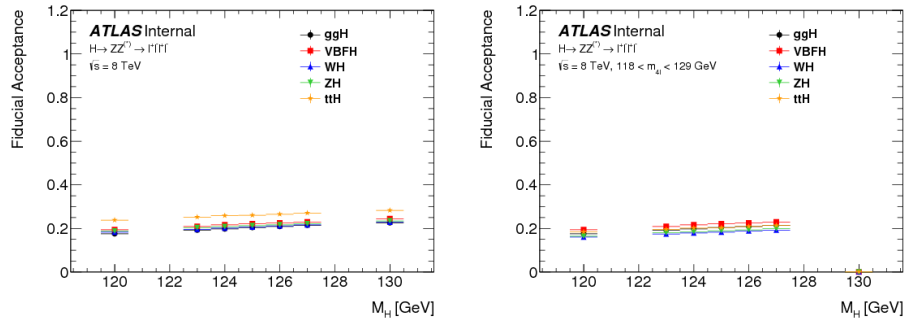


Figure 4.5: Fiducial acceptance as a function of the Higgs mass for all production modes (left) without a mass window cut and (right) with the mass window cut of $118 < m_{4\ell} < 129$ GeV.

channel (without including the $Z \rightarrow \tau\tau$ decays) as a function of m_H (Figure 4.6). In the ggH mode, the 4μ channel has the largest fiducial acceptance

while the $4e/2\mu 2e$ has the smallest acceptance due to the less strict kinematic requirements on muons as compared to electrons. In the ttH mode, once again we can see the effect of the mispairing as the $4e$ channel has larger acceptance than the mixed channels.

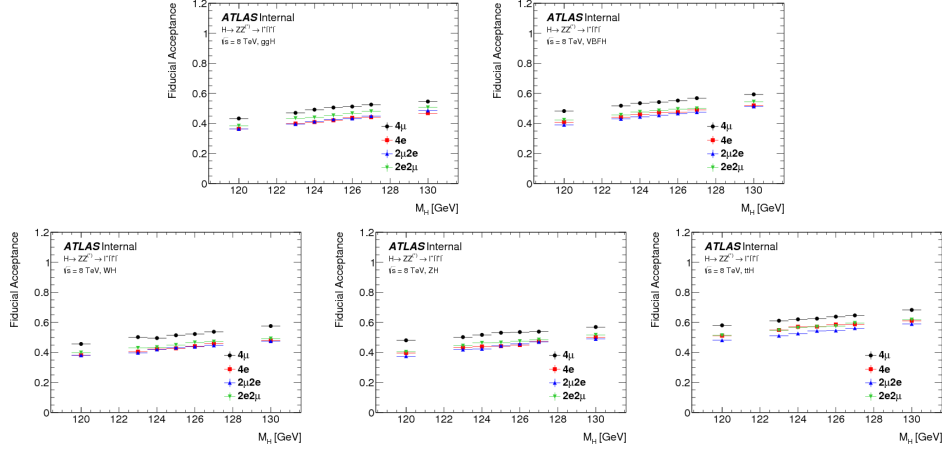


Figure 4.6: Fiducial acceptance as a function of the Higgs mass separately for each channel and each production mode. From the top left to the bottom right: ggH, VBFH, WH, ZH and ttH .

Fiducial Efficiency

The fiducial efficiency is defined as the number of reconstructed events divided by the number of fiducial events.

$$\epsilon_{fid} = N_{reco}/N_{fid} \quad (4.6)$$

In an ideal case, the fiducial efficiency will be independent of the underlying model and thus so the fiducial cross-section measurement. Furthermore, the fiducial efficiency is not an efficiency in its strictest sense as the reconstructed events are not a subset of the fiducial events (due to the fiducial leakage: the fraction of reconstructed events that are not within the fiducial region).

The Fiducial efficiency has been therefore studied for each production mode and as a function of m_H (Figure 4.7).

The fiducial efficiency ends to be the same for all production modes within 2-3%, with the exception of the ttH mode, which has a reduced efficiency with respect to the others. The reduced fiducial efficiency in ttH is the result of a decreased reconstruction efficiency due to absence of the lepton isolation requirements in the fiducial volume definition. The reconstructed leptons in ttH are less isolated because of the presence of the additional top

decays within the event: this affects leptons at the reconstructed level but not at the fiducial level and causes a different fiducial efficiency. Figure 4.7 shows that the the fiducial efficiency changes $< 1\%$ over the range $120 < m_H < 130$ GeV, indicating that the choice of Higgs mass used to derive the fiducial efficiency will introduce a negligible systematic uncertainty, while, after the mass window cut shows a stronger dependence on m_H , which is expected being the mass window cut optimized for $m_H = 125$ GeV. However, given that the uncertainties on the observed Higgs mass are at the level of 1 GeV³, the relevant points to consider are from $m_H = 124$ to $m_H = 126$ GeV. Over this range, the fiducial efficiency within the mass window changes by $< 3\%$ and a systematic uncertainty has been applied to account for this variation. The final fiducial efficiency is determined using a

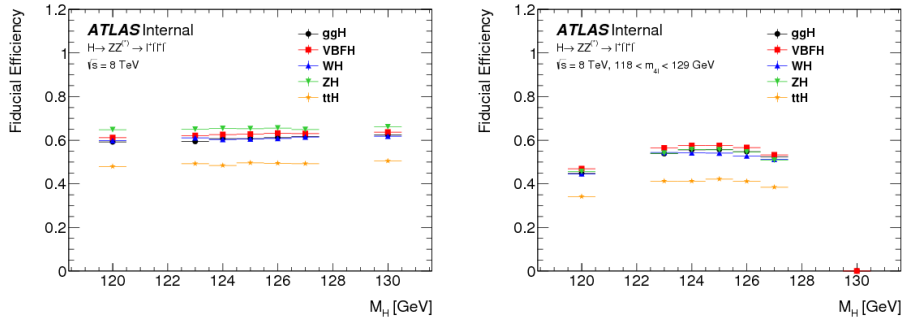


Figure 4.7: Fiducial efficiency as a function of m_H for all production modes (a) without a mass window cut and (b) with the mass window cut of $118 < m_{4\ell} < 129$ GeV.

weighted sum of the fiducial efficiencies for each production mode according to the SM cross section prediction [4].

Table 4.3 gives the fiducial efficiencies for all production modes together with the combined one.

Of course, this combination of the fiducial efficiencies for the different production modes introduces a model dependence into the measurement because the cross sections of the individual Higgs production modes are not precisely measured experimentally: a systematic uncertainty has been introduced to account for a possible bias in this procedure, and it has been evaluated by varying the contributions from the various SM production modes (Section 4.4.2.2).

Mispair Fraction

A mispaired event, as already mentioned, is basically an event in which the

³The uncertainties on the observed Higgs mass were at the level of 1 GeV when the measurements were performed (i.e. 2014), now those are at the level of 200 MeV.

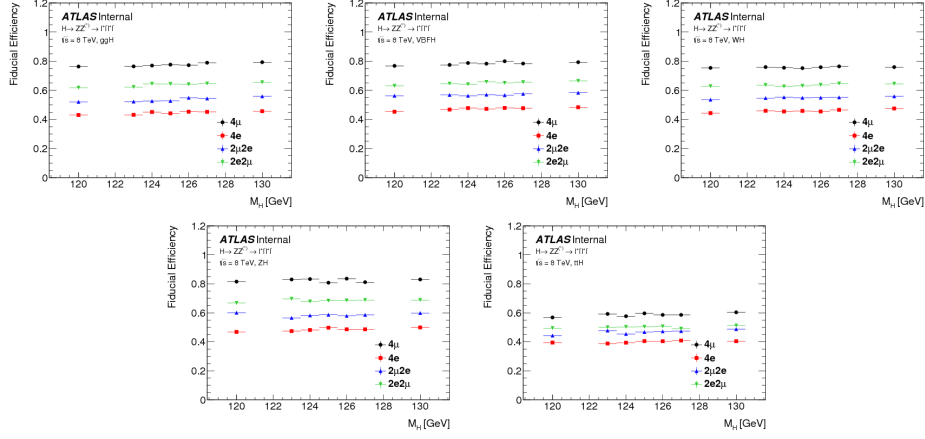


Figure 4.8: Fiducial efficiency as a function of m_H for all production modes and channels.

M_H [GeV]	Fiducial Efficiency					
	ggH	VBFH	WH	ZH	ttH	Combined
124	0.556 ± 0.003	0.575 ± 0.003	0.542 ± 0.004	0.557 ± 0.004	0.412 ± 0.004	0.557 ± 0.002
125	0.557 ± 0.003	0.576 ± 0.003	0.541 ± 0.004	0.555 ± 0.005	0.395 ± 0.004	0.557 ± 0.002
126	0.548 ± 0.003	0.566 ± 0.003	0.528 ± 0.004	0.545 ± 0.004	0.411 ± 0.004	0.548 ± 0.002

Table 4.3: Signal fiducial efficiency per production mode for signals from $M_H = 123$ GeV to 127 GeV with the mass window $[118, 129]$ GeV applied. Errors are due to MC stat only.

truth leptons in the leading and/or sub-leading pair do not share the same mother truth particle. This can occur for two reasons:

- incorrect lepton assignment to Z_1 and Z_2 in the same flavor channels (internal mispairing);
- selection of leptons which are not direct decay products of the Higgs but instead are present due to the decay of particles produced in association with the Higgs (external mispairing).

Internal mispairing strongly affects variables related to the Higgs decay to four leptons (m_{34} and $\cos(\theta^*)$, which is the angle between the Z_1 and the beam axis) and weakly affects $m_{4\ell}$ in the reconstruction due to the use of the Z mass constraint (which also relies on the definition of Z_1), while external mispairing strongly affects $m_{4\ell}$, which causes events to move in and/or out of the $m_{4\ell}$ window ([118., 129.] GeV).

It is therefore interesting to study the truth lepton multiplicity in the fiducial region for all production modes which is shown in Figure 4.9 and gives the following information:

- the ggH and VBFH modes have the lowest average multiplicity and similar distributions;
- the VH modes have slightly higher average multiplicity due to the possibility of producing leptons from the decay of the associated vector boson;
- the ttH mode has the highest average multiplicity, which will lead to a higher mispairing fraction as compared to the other production modes.

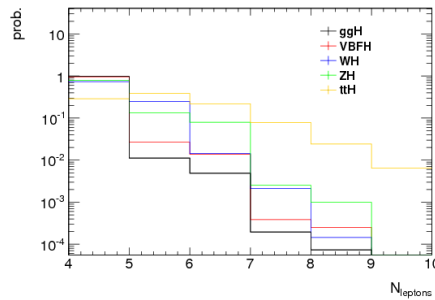


Figure 4.9: Truth lepton multiplicity distributions for fiducial events normalized to unity for all production modes assuming $m_H = 125$ GeV.

The mispairing fraction of the fiducial events has been then studied for each production mode both with and without the mass window cut (Figure 4.10),

showing that, without applying the mass window cut, the mispairing fraction is significantly higher in the VH and ttH production modes as compared to the ggH and VBF modes, as expected from the lepton multiplicity comparisons, while, within the mass window, the mispairing fraction is greatly reduced for the VH and ttH production modes, even if the reconstruction efficiency is reduced.

This feature is generally expected since the external mispairing will result in an $m_{4\ell}$ not correlated with the Higgs mass and thus will have a higher probability of falling outside of the mass window. The mispairing fraction

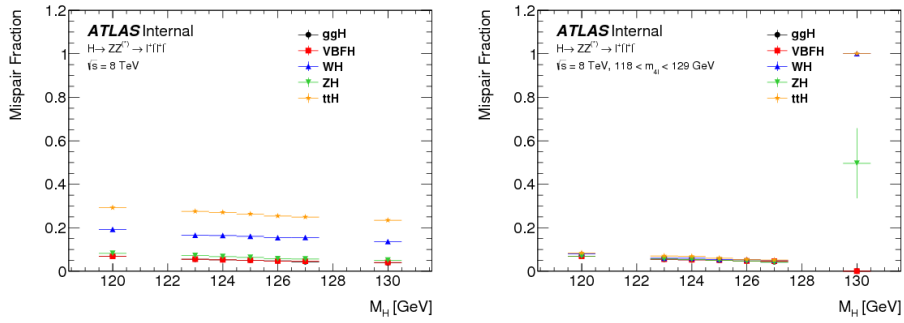


Figure 4.10: Fiducial mispair fraction as a function of m_H for all production modes (a) without a mass window cut and (b) with the mass window cut of $118 < m_{4\ell} < 129$ GeV.

has been also investigated as a function of m_H (Figure 4.11) for all production modes and channels separately. In the ggH and VBFH modes, it is clear that the predominant effect is the internal mispairing as the mispairing fraction is nearly zero for the mixed flavor channels; however, in the VH and ttH modes, there is evidence of external mispairing as the mixed channels do have a non-zero mispairing fraction.

Fiducial Leakage

The fiducial leakage, defined as the fraction of reconstructed events which are not within the fiducial region, is used to determine whether the fiducial region cuts are well defined. It is expected to be non-zero due to detector and reconstruction effects, causing event migration at the edge of the fiducial region.

Leakage events are events produced by signal processes but considered as background since they lie outside the fiducial region.

Looking at the fiducial leakage for all production modes with and without the mass window cut (Figure 4.12), the results without the mass window cut shows that the leakage is $<10\%$ for all samples and $<5\%$ for the ggH production mode.

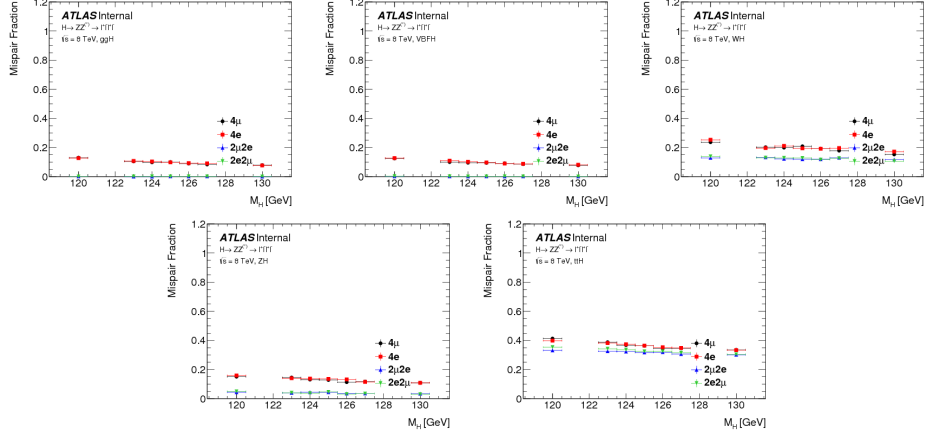


Figure 4.11: Fraction of fiducial events which are mispaired as a function of the Higgs mass for all production modes.

ZH and ttH modes have roughly twice the fiducial leakage of the other modes since:

- the ZH mode has higher leakage due to $ZH \rightarrow 4\ell 2\tau$ decays, in which the τ s are decay products of the Higgs boson (events which are excluded from the fiducial selection).
- the increased lepton multiplicity in the ttH mode results in larger fiducial leakage as compared to the fiducial leakage in the ggH mode.

Adding the mass window cut, the leakage is $<5\%$ for all production modes at $m_H = 125$ GeV.

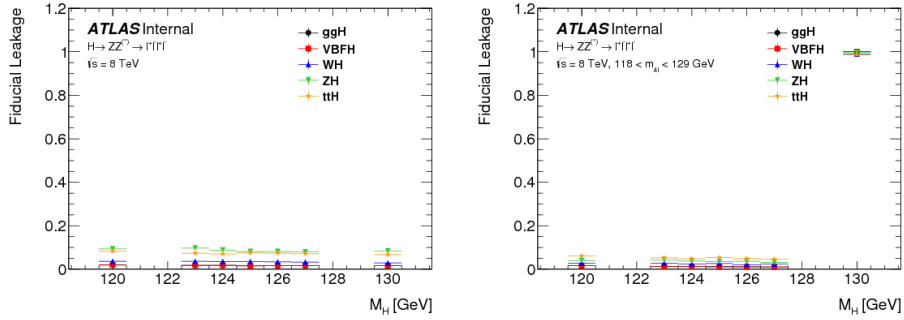


Figure 4.12: Fiducial leakage as a function of m_H for all production modes (a) without a mass window cut and (b) with the mass window cut of $118 < m_{4\ell} < 129$ GeV.

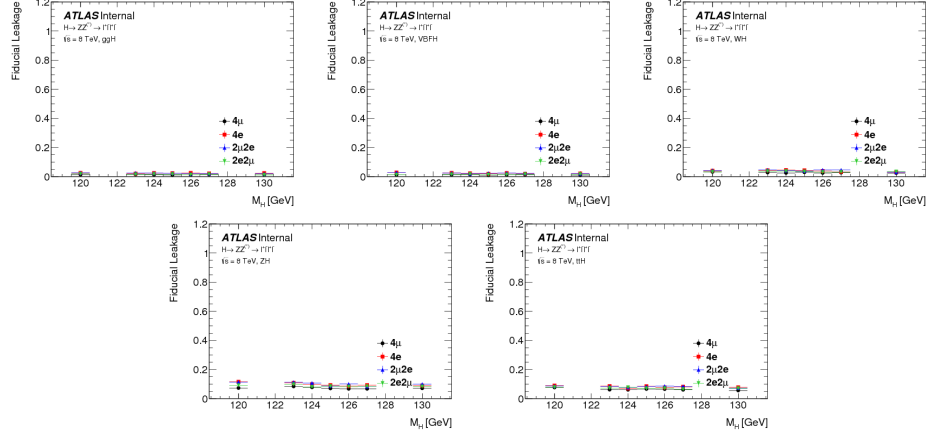


Figure 4.13: Fiducial leakage as a function of the Higgs mass for all production modes.

Combined Fiducial Efficiency

The final fiducial efficiency is determined by combining the N_{reco} and N_{fid} of the various production modes according to their SM cross sections and calculating a combined fiducial efficiency (Section 1.3.1).

The fiducial efficiency has then been evaluated at $m_H = 125.4$ GeV (as measured in the ATLAS mass combination at 8 TeV [42]) by performing a linear interpolation between the two nearest mass signal points (125 and 126 GeV). Table 4.4 gives the inclusive correction factor (equal to $1/\epsilon_{fid}$) both with and without the mass window and for each mode separately.

Mode	Correction Factor	Correction Factor ($m_{4\ell}$ in [118,129] GeV)
ggH	1.643 ± 0.005	1.808 ± 0.007
VBF	1.589 ± 0.005	1.748 ± 0.006
WH	1.65 ± 0.007	1.868 ± 0.01
ZH	1.53 ± 0.007	1.814 ± 0.011
ttH	2.018 ± 0.01	2.396 ± 0.016
Combined	1.639 ± 0.005	1.808 ± 0.006 (stat) ± 0.049 (syst)

Table 4.4: Inclusive correction factors with and without the mass window cut evaluated at $m_H = 125.4$ GeV. Uncertainties on the individual production modes are statistical only.

4.3.3 Variables and binning for differential cross section measurements

Six observables related to the Higgs boson production and decay are selected to be sensitive to its properties as follows:

- the $p_{T,H}$ is sensitive to the Higgs boson production mode and spin/ $\mathcal{CP}$ quantum numbers, and can be used to test perturbative QCD predictions;
- $|y_H|$ depends on QCD radiative corrections and can be used to probe the proton parton distribution functions (PDF);
- m_{34} and $|\cos(\theta^*)|$ ⁴ are sensitive to the Lagrangian structure of Higgs boson interactions (spin/ $\mathcal{CP}$ quantum numbers and higher order operators);
- the jet distributions (n_{jets} and $p_{T,jet1}$) are sensitive to both QCD radiation effects and the relative rates of Higgs boson production modes.

The fraction of events coming from non-ggH production modes increases with the jet multiplicity due to the presence of hadronic decays of the particles produced in association with the Higgs boson or forward jets associated to the event as for the VBFH (Figure 4.18); this allows measurement of the relative strength between the ggH, VBFH, VH, and ttH couplings. As shown in Figure 4.18, the 0-jet bin is dominated by ggH production while VH and VBFH production modes contribute increasingly larger fractions in the 1-jet and 2-jet bins, while the majority of ttH events have high jet multiplicity ($N_{jets} \geq 3$).

Binning The binning is chosen for each variable of interest before looking to the data signal region ($118 < m_{4\ell} < 129$ GeV) based on several criteria:

- first, the range of each variable is chosen (for fixed range variables, such as $|\cos(\theta^*)|$, this is trivial; for variables with unbound ranges such as $p_{T,H}$, the range is chosen to cover approximately 95% of the events from the expected SM signal (overflow events are also reported).)
- the number of bins is chosen in order to achieve an expected significance of roughly 1.5σ in each bin. Within the signal region, $S/\sqrt{S+B}$ is expected to be approximately 3 in the SM with the current data set, and, assuming that significances add in quadrature, a rough approximation gives $3^2/1.5^2 = 4$ bins for each variable.

Table 4.5 lists the chosen binning for all of the variables, which is extensively explained in the following:

⁴ m_{34} is the invariant mass of the off-shell Z boson and $|\cos(\theta^*)|$ is the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis.

- $p_{T,H}$: Bin edges are suggested by theoretical concerns. For $p_{T,H} > 100$ GeV, the calculation of the ggH cross-section can be accomplished using a fixed order calculation, but below 100 GeV, the calculation requires resummation of leading order logarithms. Furthermore, the treatment of the finite top and bottom quark mass creates additional scales, one at twice the b quark mass.
- $|y|_H$: The rapidity distribution is fairly flat and thus allows for five bins,
- m_{34} : The lower edge of the distribution is bounded by the $m_{34} > 12$ GeV cut which is applied in the event selection; the bin edges are then placed at multiples of 10 GeV from 20 GeV to 60 GeV. The last two bins (40-50, 50-60 GeV) are combined in order to improve the statistical significance.
- $|\cos(\theta^*)|$: This distribution is flat in the SM and thus a fixed width binning is chosen with a width of 0.2.
- N_{jets} : Trivial binning, except for the highest bin which is inclusive in order to decrease the effects of bin-to-bin migrations at high N_{jets} where there are large theoretical uncertainties in the modeling due to the use of perturbative calculations.
- $p_{T,jet}$: mainly chosen to harmonize with other analysis in view of future combination of the results.

Variable	Bin Edges	N_{bins}
$p_{T,H}$	0, 20, 50, 100, 200 GeV	4
$ y _H$	0, 0.3, 0.65, 1.0, 1.4, 2.4	5
$ \cos(\theta^*) $	0, 0.2, 0.4, 0.6, 0.8, 1.0	5
m_{34}	12, 20, 30, 40, 60 GeV	4
N_{jets}	0, 1, 2, ≥ 3	4
$p_{T,jet}$	0, 30, 50, 70, 140 GeV	4

Table 4.5: Binning chosen for the variables of interest. Overflow events are reported but do not contribute to the measurement.

4.3.4 Background estimate

The backgrounds are grouped into two categories:

- irreducible backgrounds which have nearly identical final states as the signal process due to the presence of four prompt leptons;
- reducible backgrounds for which some leptons of the quadruplets are produced by heavy flavor decays or as misidentified hadrons.

4.3.4.1 Irreducible background

The irreducible SM $ZZ^{(*)} \rightarrow 4\ell$ background is estimated using MC predictions as described in Chapter 3.

The main production mechanism in the 4ℓ -mass region selected in this analysis is predicted to be qq annihilation and the normalization for this background is taken from theory prediction with an associated uncertainty of 4%. In addition, a small contribution from the gluon-gluon annihilation process has been also added normalized to theory predictions with a normalization uncertainty of 30%. This gluon-gluon production contribution is expected to be very small in the signal mass window (at the level of less than 2% of the qq contribution) and the interference between the $gg \rightarrow ZZ^*$ and the $gg \rightarrow H \rightarrow ZZ^*$ signal is expected to be below 1% in the signal mass window [46] and is neglected in this analysis.

To verify that the simulation correctly models the variables that will be used for the measurements and that will be unfolded, the MC predictions are checked in the high mass control region: requiring $m_{4\ell} > 190$ GeV less than 1% contamination from reducible backgrounds is present. Good agreement is observed in all the chosen variables (Figure 4.14).

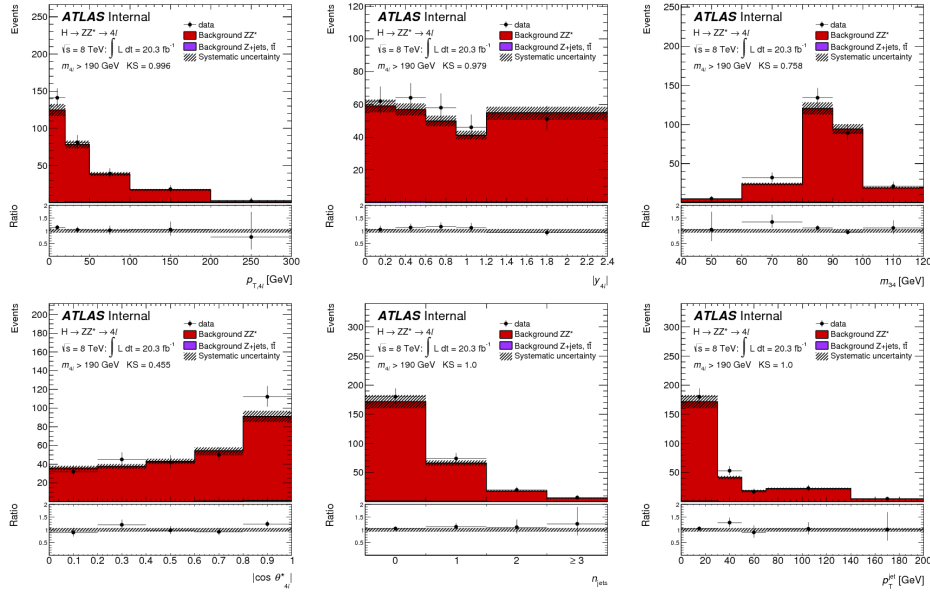


Figure 4.14: MC predictions and data yields in the high mass control region ($m_{4\ell} > 190$ GeV).

4.3.4.2 Reducible background

Reducible backgrounds are due to processes such as $Z + jets$ and $t\bar{t}$ production, in which charged lepton candidates originate from semi-leptonic decays of heavy flavor hadrons, or from mis-identification of jets as leptons.

These backgrounds are estimated using data-driven methods by extrapolating the yields from a data control region into the signal region using data-driven efficiency factors. Separate extrapolations are done for events with subleading muons and subleading electrons due to the different composition of the backgrounds in these channels as described in Chapter 3.

A brief outline of the baseline method for each sub-channel decay is reported.

Subleading di-muon channels For the subleading di-muon channels, the background yields are determined using a simultaneous unbinned maximum likelihood fit of the m_{12} distribution in four control regions, which are orthogonal to one another, as well as to the signal region. Three of the control regions are chosen to be enriched in specific background processes, while the fourth contains contributions from all of the main backgrounds.

- **Inverted d_0 control region.** The leading dilepton must pass the standard analysis selection, while for the subleading dilepton, the isolation requirement is dropped and the impact parameter significance parameter requirement is inverted for at least one lepton. This yields a sample enriched in $Zb\bar{b}$.
- **Inverted isolation control region.** This control region, enriched in $Z + light\ jets$, requires the leading dilepton to pass the standard analysis selection, while the isolation requirement is inverted for at least one of the subleading dileptons.
- **$e\mu + \mu\mu$ control region.** The leading dilepton consists of an opposite-sign, different-flavour pair passing the standard analysis selection, plus a same-flavour subleading pair having either the same or opposite signs. The isolation and impact parameter significance cuts are not applied on the subleading pair. This control region is therefore enhanced in $t\bar{t}$ events.
- **Same-sign control region.** This control region, consisting of events with leading dilepton pairs passing the standard analysis selection and same-sign subleading lepton pairs not required to satisfy the isolation or impact parameter significance cuts, contains contributions from all of the main backgrounds.

The number of events in each control region can be expressed as a function of the number of events of that component in a fifth control region, known as the relaxed opposite-sign control region, in which the isolation and impact

parameter significance cuts are relaxed for the subleading dilepton pair. This control region contains contributions from all of the backgrounds, but is not used in the fit since it also contains the signal region.

The background contributions are determined using an unbinned maximum likelihood fit of the m_{12} distribution for data; this is done simultaneously for the four control regions described above. The $t\bar{t}$ distribution is modelled by a second-order Chebyshev polynomial and the $Zb\bar{b}$ and $Z + \text{light jets}$ shapes are modelled by convoluting a Breit-Wigner distribution with a Crystal Ball function.

For each control region, the fit model is given by:

$$\text{PDF}_{\text{fitCR}} = N_{t\bar{t}}^{\text{OSCR}} \cdot f_{t\bar{t}} \cdot M_{t\bar{t}} + N_{Zb\bar{b}}^{\text{OSCR}} \cdot f_{Zb\bar{b}} \cdot M_{Zb\bar{b}} + N_{Z\text{light}}^{\text{OSCR}} \cdot f_{Z\text{light}} \cdot M_{Z\text{light}} + N_{ZZ+WZ}^{\text{OSCR}} \cdot f_{ZZ+WZ} \cdot M_{ZZ+WZ} \quad (4.7)$$

where M_x is the model of a particular background x and f_x is the ratio of that background in the given control region and the relaxed opposite-sign control region. The reducible background contributions in the relaxed opposite-sign control region are estimated from simulation and from the fit and are shown in Table 4.6. The signal region yield is determined

Reducible Background	MC prediction	Fit estimation	Scaling
$Zb\bar{b}$	93.5 ± 0.7	139 ± 16	1.49
$Z + \text{light}$	43 ± 5	46 ± 9	1.07
$t\bar{t}$	150.6 ± 1.5	181 ± 11	1.20

Table 4.6: Estimations of the $2l2\mu$ reducible background contributions in the relaxed opposite-sign control region as predicted from the simulation and estimated from the fit. The resulting required scaling with respect to the MC normalization prediction is also quoted.

by applying a simulation-based transfer factor (cross-checked in data) to the control region yields; this factor is defined as the probability for a given event of a particular background type to pass the isolation and impact parameter significance cuts.

Reducible background shapes in both the signal and control regions for the variables of interest are taken from the simulation and validated in CRs; in addition, the $Z + \text{jets}$ and $t\bar{t}$ contributions are reweighted to match the measured data yields in the control region.

The final estimates of the reducible backgrounds in the signal region are given in Table 4.7. The statistical error corresponds to the uncertainty on the fit, and the systematic error is given by the efficiency factor uncertainty. Figure 4.15 shows the variables of interest in the inverted impact parameter significance control region: good agreement is observed between data and MC.

Reducible Background	4μ	$2e2\mu$
$Zb\bar{b}$	$2.30 \pm 0.26(\text{stat}) \pm 0.14(\text{syst})$	$2.01 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})$
$Z + \text{light}$	$0.81 \pm 0.38(\text{stat}) \pm 0.41(\text{syst})$	$0.57 \pm 0.31(\text{stat}) \pm 0.41(\text{syst})$
Total $Z + \text{jets}$	$3.11 \pm 0.46(\text{stat}) \pm 0.43(\text{syst})$	$2.58 \pm 0.39(\text{stat}) \pm 0.43(\text{syst})$
$t\bar{t}$	$0.511 \pm 0.031(\text{stat}) \pm 0.089(\text{syst})$	$0.485 \pm 0.029(\text{stat}) \pm 0.085(\text{syst})$

Table 4.7: Estimated $2l2\mu$ reducible background contamination in the signal region, for the full mass range. The systematic uncertainties are estimated from the transfer factor error, which contains the efficiency difference observed in the 3ℓ final state (1.6%).

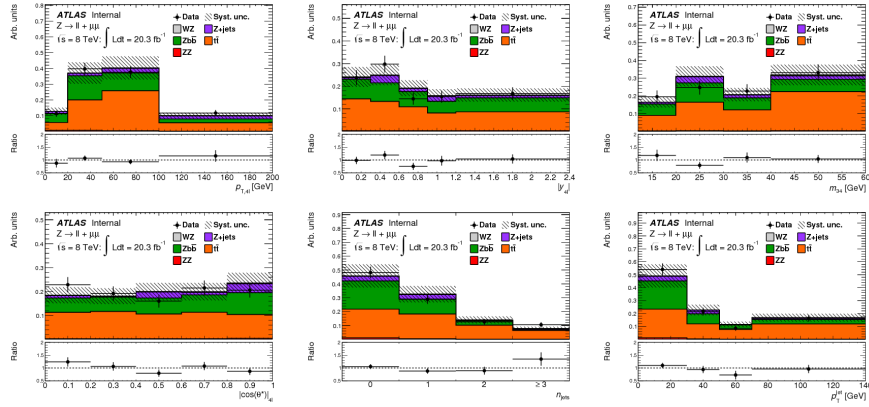


Figure 4.15: Comparison of variable shapes in data and simulation for the inverted impact parameter significance control region. Data-driven normalization scaling factors are applied to the simulated $Z + \text{jets}$ and $t\bar{t}$ samples. The shapes are normalized to unity.

Subleading di-electron channels In the channels with two subleading electrons, the main source of reducible background is due to jets being misidentified as electrons. The baseline method for extrapolating this background, the so called $3\ell + X$ method, relies on a control region consisting of quadruplets having the three highest- p_T leptons passing the standard analysis cuts, while the lowest- p_T lepton, denoted as X , is only required to pass the standard silicon hit requirements. The subleading di-leptons are required to have the same electromagnetic charge in order to veto the irreducible ZZ^* contribution. A two-dimensional template fit is performed on the distributions of the number of B-layer hits (n_{BL}) and the TRT high threshold ratio ($rTRT$) in data in order to disentangle the contributions of the various background contributions: jets faking electrons (f), photon conversions and FSR (γ), and semi-leptonic heavy quark decays (q). To extrapolate from the control region to the signal region, transfer factors are calculated using selection efficiencies derived from simulated $Z + X$ events, consisting of an on-shell Z boson decaying to two leptons, accompanied by an electron candidate passing the standard silicon hit requirement. Efficiencies are calculated for fakes, conversions, and heavy quark decays. The efficiencies for fakes and conversions are corrected using data / MC scale factors derived from highly-enriched control regions in order to account for differences between simulation and data. For fakes and conversions, the transfer factors are defined as:

$$TF = \sum_{i=\gamma, f} \epsilon^i(p_T) \times w_{sPlot}^i$$

where the w_{sPlot}^i correspond to the probability of an X to belong to a particular background component, and the $\epsilon^i(p_T)$ are the p_T -dependent efficiencies for the different components. Due to large statistical fluctuations in the heavy flavour component, an inclusive transfer factor is derived from simulation:

$$TF_q = \frac{n_{SR}}{n_{CR}}$$

Table 4.8 shows the expected yield of the three main background components in the control region, as well as the average efficiencies for each component and the extrapolated yield in the signal region. A small residual contribution from the irreducible ZZ^* background is determined from simulation, and is subtracted to give the final yield in the signal region, as shown in Table 4.9.

The shapes of the variables of interest are shown in Figure 4.16: good agreement is shown between data and MC.

For both channels, the normalization of the reducible backgrounds is determined by multiplying the inclusive reducible background yield estimates (which are integrated over the entire mass range) by an efficiency factor to

4e				
type	data fit	efficiency	SR yield	
f	420.0 ^{+21.50} _{-21.20}	0.0034 ± 0.0004	1.45	^{+0.07} _{-0.07} ^{+0.47} _{-0.47}
q	7.60 ^{+1.51} _{-1.52}	0.11 ± 0.02	0.83	^{+0.18} _{-0.18} ^{+0.14} _{-0.14}
γ	29.36 ^{+8.28} _{-7.75}	0.024 ± 0.004	0.68	^{+0.20} _{-0.20} ^{+0.20} _{-0.20}
2 μ 2e				
type	data fit	efficiency	SR yield	
f	473.7 ^{+22.8} _{-22.4}	0.0034 ± 0.0004	1.65	^{+0.08} _{-0.08} ^{+0.53} _{-0.53}
q	10.66 ^{+2.13} _{-2.13}	0.09 ± 0.02	0.96	^{+0.26} _{-0.26} ^{+0.16} _{-0.16}
γ	18.2 ^{+7.80} _{-7.19}	0.024 ± 0.004	0.43	^{+0.19} _{-0.19} ^{+0.21} _{-0.21}

Table 4.8: $2\ell 2e$ reducible background estimate: Fit results for the yield of each background component (hadronic jets faking electrons, electrons from heavy flavor, conversions) estimated from the 2D template fit to the data in the $3\ell + X$ control region. The average extrapolation efficiencies for each component are shown together with the yield in the signal region. The uncertainties on the SR yield are statistical and systematic.

	4e	2 μ 2e
Extrapolation SR	2.96±0.61	3.04±0.69
ZZ^* extrapolation	0.08±0.01	0.13±0.01
Final estimation	2.88±0.61	2.91±0.69

Table 4.9: Reducible background estimation, along with the estimated ZZ^* contribution in the signal region, derived using the $3\ell + X$ method. The last row quotes the final estimate after subtracting the ZZ^* contribution.

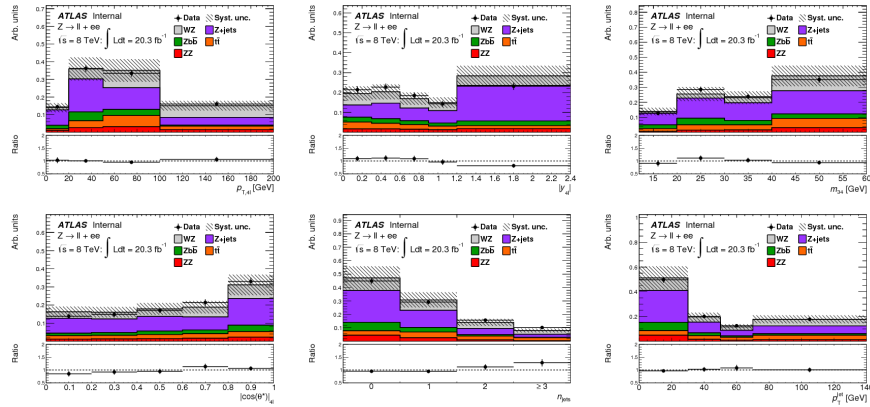


Figure 4.16: Comparison of variable shapes in data and simulation for the $3\ell + X$ control region. The shapes are normalized to unity.

account for the mass window cut. This factor is calculated using the $m_{4\ell}$ shape as derived in each channel to determine the fraction of events which fall within the mass window and it is determined to be 0.191 (0.137) in the muon (electron) channels.

The shape of the reducible background in the variable of interest is determined by extrapolating the control region yields within the mass window to the signal region using the transfer factors.

4.3.5 Expected signal yields

The expected reconstructed signal yields for $m_H = 125$ GeV are derived using the Higgs signal samples and cross-sections described in Sec. 3.1. Trigger and lepton efficiency corrections are applied to account for differences between the simulation and the data.

The inclusive expected number of signal events for each Higgs production mode can be seen in Table 4.10 while the expected number of signal events in each differential bin can be seen in Figure 4.17. Figure 4.18 finally shows the production mode composition of signal events in each bin for all variables of interest.

20.3 fb ⁻¹ @ $\sqrt{s} = 8$ TeV, $118 < m_{4\ell} < 129$ GeV					
ggH	VBFH	WH	ZH	ttH	Total
12.26 $\pm$ 0.09	1.125 $\pm$ 0.008	0.391 $\pm$ 0.004	0.245 $\pm$ 0.003	0.0569 $\pm$ 0.0007	14.07 $\pm$ 0.09

Table 4.10: Number of expected reconstructed signal events for each Higgs production mode assuming $m_H = 125$ GeV within the mass window [118, 129] GeV for 20.3 fb⁻¹ at $\sqrt{s} = 8$ TeV, as obtained with the samples and cross-sections described in Sec. 3.1. Errors are from MC stat only.

4.3.6 Unfolding procedure

The unfolding procedure has been used in order to determine the truth distributions from the observed ones.

The relation between the truth and reconstructed variables has been characterized using the detector response matrix shown in Fig. 4.19. Concerning the kinematic variables, the response matrix is nearly diagonal because the detector resolution is much smaller than the bin width and bin-to-bin migrations are of order 10% or less for these variables, while for the jet variables, the bin-to-bin migrations are found to be larger, up to 50% in some bins.

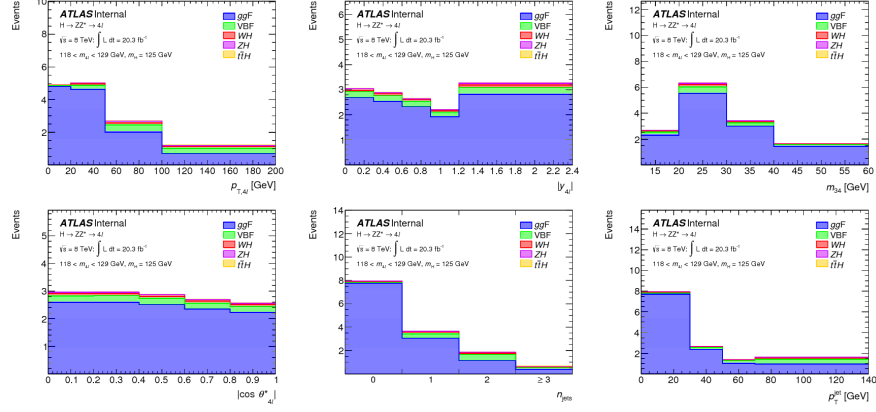


Figure 4.17: Expected number of reconstructed signal events within the mass window [118,129] GeV in all variables of interest assuming a SM Higgs with $m_H = 125$ GeV. The five production modes are plotted separately, with ggH as the dominant production mode.

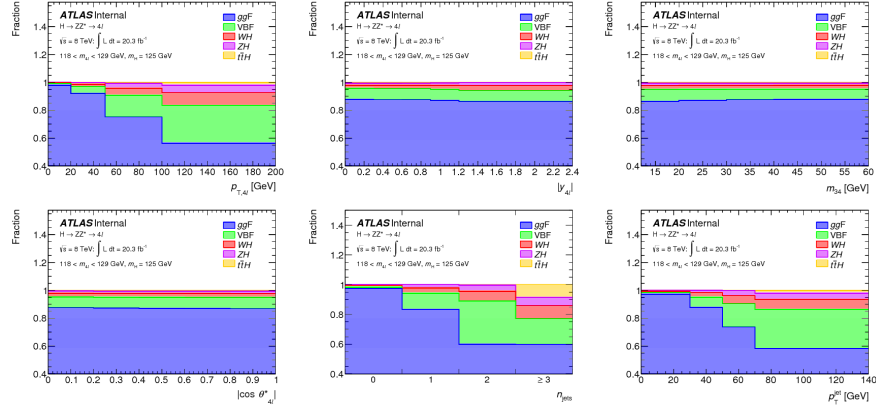


Figure 4.18: Signal production mode composition within the mass window [118,129] GeV in all variables of interest assuming a SM Higgs with $m_H = 125$ GeV.

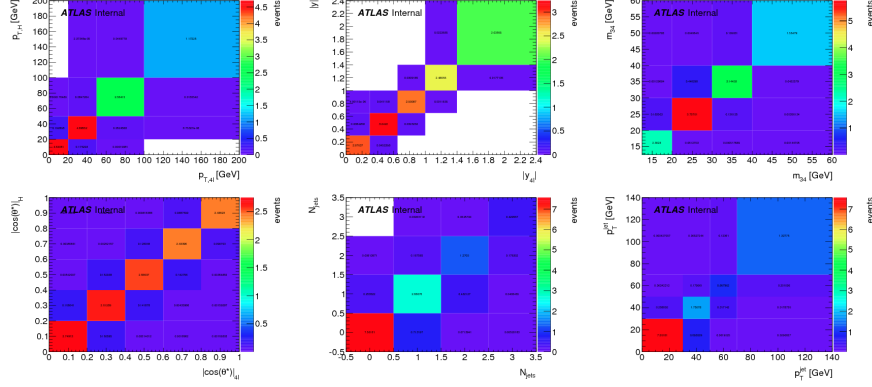


Figure 4.19: Response matrices for all variables of interest using the Higgs signal samples with $m_H = 125$ GeV. The number of events is plotted as a function of reconstructed and truth variables.

Bin-by-bin Correction Factors

The correction factor are defined bin-by-bin as:

$$CF_i = \frac{N_i^{fid}(x_{truth})}{N_i^{reco}(x_{reco})}, \quad (4.8)$$

where $N_i^{fid}(x_{truth})$ is the number of fiducial events in the i -th bin of the truth distribution and $N_i^{reco}(x_{reco})$ is the number of events in the i -th bin of the reconstructed distribution.

The correction factors account for both detector efficiencies and bin-to-bin migrations and are derived from the signal simulation using the SM prediction for the cross sections of the various Higgs production modes. A systematic uncertainty is assigned to account for the lack of knowledge of the exact signal production mode composition, as detailed in Section 4.4.2.2. The correction factor method is known to introduce a bias into the measurement because CFs are derived from the signal simulation and therefore are model dependent. This bias can be quantified as [47]:

$$\langle \delta\mu_i \rangle = s_i \times \left(\left(\frac{\mu_i}{s_i} \right)_{Model} - \left(\frac{\mu_i}{s_i} \right)_{Truth} \right), \quad (4.9)$$

where μ_i is the number of true events, s_i is the number of reconstructed signal events, and $\langle \delta\mu_i \rangle$ is the average bias in the i -th bin. It is difficult to estimate it, as it depends on the difference between the truth and the model, which is not known *a priori*, however, it can also be shown that the bias is proportional to the off-diagonal terms of the response matrix:

$$\langle \delta\mu_i \rangle = s_i \times \sum_{j \neq i} R_{ij}^{-1} \left(\left(\frac{s_j}{s_i} \right)_{Model} - \left(\frac{s_j}{s_i} \right)_{Truth} \right). \quad (4.10)$$

Therefore, the size of this bias goes to zero as the response matrix becomes diagonal (in other words, the bin-to-bin migrations are small). The usage of this method is therefore more easily justified for the kinematic variables of interest and systematic uncertainties are therefore assigned to cover possible variations in the signal model (Sec. 4.4.2.2). Checks have been carried out also on the correction factor dependency on different spin/ $\mathcal{CP}$ hypothesis. The JHU (LO) generator has been used for this purpose and the ratio of the CFs for $J_{alt}^P = 0^-$ and 2^+ hypothesis with respect to the JHU SM prediction $J_{SM}^P = 0^+$ is shown in Figure 4.20. The comparison between the JHU and Powheg (NLO) generators is also reported for the SM hypothesis. As shown, the spin/ $\mathcal{CP}$ hypothesis dependence of the CF lies within the statistical errors (5% compatible between each other), therefore no systematic needs to be included. Correction Factors derived for

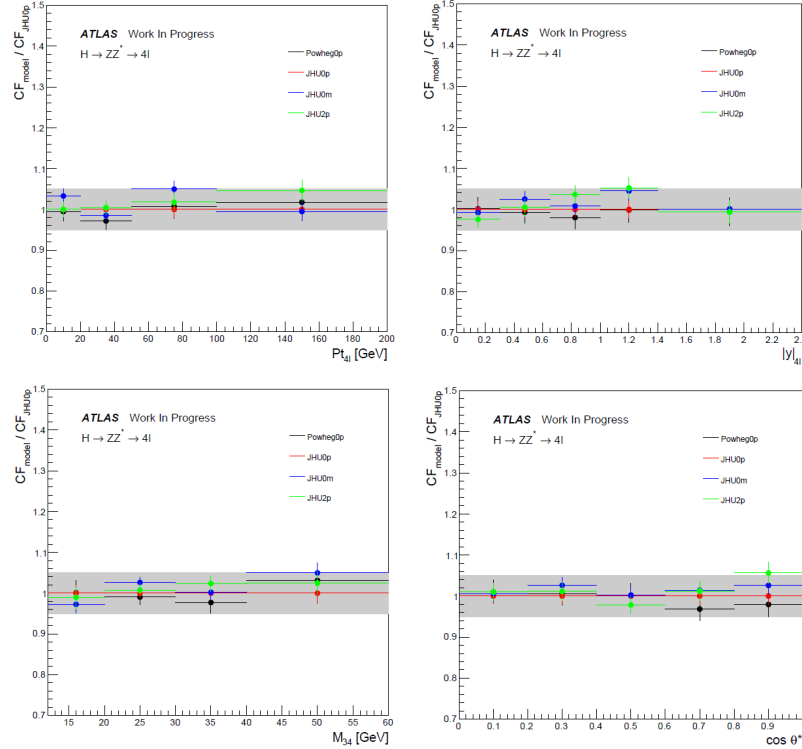


Figure 4.20: Ratio of correction factors for different spin/ $\mathcal{CP}$ hypothesis (JHU 0^- and 2^+) with respect to the JHU SM prediction. The 0^+ case generated with Powheg has also been tested. The grey line denotes the 5% band width.

each production mode and variable are shown in Figure 4.21. The combined CFs with weights proportional to the SM cross section of each production

mode (Figure 4.22) are used in the analysis and summarized in Table 4.11. It can be seen that the correction factors are flat in the variable of interest, except for the N_{jets} , $p_{T,jet1}$ and to a lesser extent y_H (all modes), and $p_{T,H}$ ($t\bar{t}H$). As for the inclusive fiducial cross-section, the correction factor for the $t\bar{t}H$ process differs from the other modes in all variables. Systematic

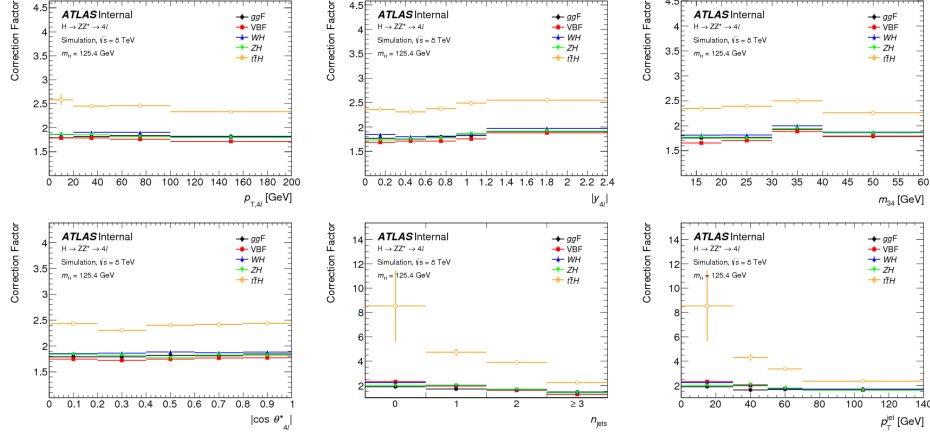


Figure 4.21: Correction factors for all Higgs production modes separately evaluated at $m_H = 125.4$ GeV. Errors are statistical only, as the systematic uncertainties are only derived for the combined correction factor.

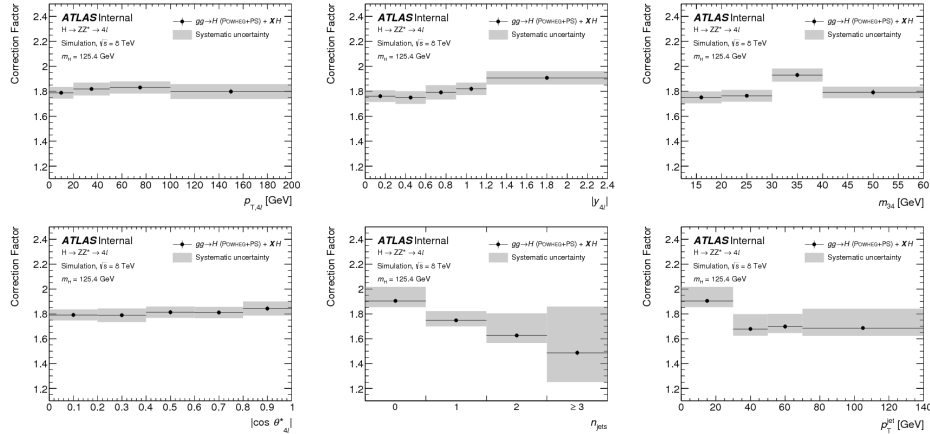


Figure 4.22: Combined correction factors evaluated at $M_H = 125.4$ GeV. All systematics are included.

error for the CF made using all PM have been also checked as follows:

- the statistical error has been estimated as the error of an efficiency with

Variable	Bin 0	Bin 1	Bin 2	Bin 3	Bin 4
$p_{T,H}$	$1.79 \pm 0.01 \pm 0.05$	$1.82 \pm 0.01 \pm 0.05$	$1.83 \pm 0.02 \pm 0.05$	$1.8 \pm 0.02 \pm 0.06$	-
$ y $	$1.76 \pm 0.02 \pm 0.05$	$1.75 \pm 0.02 \pm 0.05$	$1.79 \pm 0.02 \pm 0.06$	$1.82 \pm 0.02 \pm 0.05$	$1.91 \pm 0.02 \pm 0.05$
m_{34}	$1.75 \pm 0.02 \pm 0.05$	$1.76 \pm 0.01 \pm 0.05$	$1.93 \pm 0.02 \pm 0.05$	$1.79 \pm 0.02 \pm 0.05$	-
$ \cos\theta^* $	$1.79 \pm 0.02 \pm 0.04$	$1.79 \pm 0.02 \pm 0.06$	$1.81 \pm 0.02 \pm 0.05$	$1.81 \pm 0.02 \pm 0.05$	$1.84 \pm 0.02 \pm 0.06$
n_{jets}	$1.9 \pm 0.01^{+0.11}_{-0.05}$	$1.75 \pm 0.01^{+0.07}_{-0.05}$	$1.63 \pm 0.02^{+0.18}_{-0.06}$	$1.49 \pm 0.02^{+0.37}_{-0.24}$	-
$p_{T,jet1}$	$1.9 \pm 0.01^{+0.11}_{-0.05}$	$1.68 \pm 0.02^{+0.12}_{-0.05}$	$1.7 \pm 0.02^{+0.1}_{-0.05}$	$1.69 \pm 0.02^{+0.16}_{-0.06}$	-

Table 4.11: Combined correction factors for all variables extrapolated to $m_H = 125.4$ GeV. The first quoted error is (stat), the second is (syst).

the binomial statistics ($CF = 1/\epsilon$): $E_{stat,PM} = CF \cdot \sqrt{(CF - 1)/N_{truth}}$ and the total statistical error is therefore:

$$E_{stat,all} = \sqrt{\sum_{PM} (E_{stat,PM} \cdot (\sigma_{PM}/\sigma_{TOT}))^2};$$

- the systematic error has been computed taking as downward/upward variation: $(\sigma_{VBF+VH})_{SM} \times 0.5/2$. and $(\sigma_{t\bar{t}H})_{SM} \times 0./5$. as from previous studies [48].

Figure 4.23 shows a qualitative study of the statistical (grey band) and systematic (black bars) errors on the correction factors per production mode in the variables of interest: this study shows that the systematic error is negligible with respect to the statistical error.

4.3.7 Differential Cross-section Extraction

The likelihood function describing a binned counting experiment can be constructed as follows:

$$L = \prod_{i=0}^{N_{bins}} \text{Poisson}(n_i^{\text{obs}}; n_i^{\text{exp}}) \cdot \prod_{j=0}^{N_{syst}} \text{Gaussian}(\theta_j; 0, 1) \quad (4.11)$$

$$n_i^{\text{exp}} = s_i + \sum_{\text{bkg}} b_i \quad (4.12)$$

where n_i^{obs} is the number of observed data events and the number of expected events, n_i^{exp} , is the sum of the signal and background events in the i-th bin. The product of the Poisson PDFs from each bin is multiplied by Gaussian pdf constraints on the nuisance parameters (NP) θ_j . The backgrounds being constructed as:

$$b_i = b_i^{\text{nom}} \prod_{j=0}^{N_{syst}} (1 + \alpha_{i,j} \cdot \theta_j) \quad (4.13)$$

where b_i^{nom} is the nominal background prediction and $\alpha_{i,j}$ are the relative systematic variations (up and down) of the yield in i-th bin for the j-th systematic. Parameters for the correction factors and theory cross section

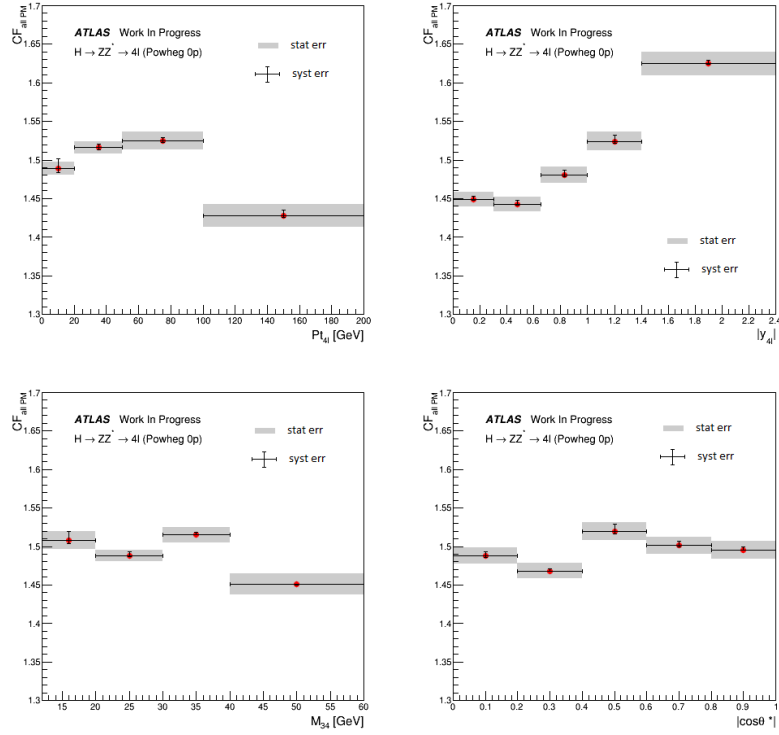


Figure 4.23: Qualitative study of the statistical (grey band) and systematic (black bars) errors on the correction factors per production mode in the variables of interest.

predictions are constructed similarly.

The signal yields in each bin can be then extracted using the profile likelihood ratio defined as follows:

$$\Lambda(s_i) = \frac{L(s_i, \hat{\hat{\theta}}(s_i))}{L(\hat{s}_i, \hat{\theta})} . \quad (4.14)$$

where the single circumflex denotes the unconditional maximum likelihood estimate of a parameter and the double circumflex (*e.g.* $\hat{\hat{\theta}}(s_i)$) denotes the conditional maximum likelihood estimate (*e.g.* of $\hat{\theta}$) for given fixed values of s_i .

The number of signal events in the i -th bin, s_i , which are used to extract the cross section measurements, can be re-formulated as a function of various parameters of interest (POI) among which the signal strength ($\mu_i = 1$ in case of SM expectations) has been widely used to make MC checks for sake of simplicity:

- $\mathbf{n}_{\text{sig},i}^{\text{reco}}$ (number of observed signal events):

$$s_i = n_{\text{sig},i}^{\text{reco}} \quad (4.15)$$

- $\mathbf{n}_{\text{sig},i}^{\text{truth}}$ (corrected number of observed signal events):

$$s_i = n_{\text{sig},i}^{\text{truth}} \cdot \frac{1}{CF_i} \quad (4.16)$$

- $(d\sigma/dx)_{i,\text{obs}}$ (observed differential cross section):

$$s_i = (d\sigma/dx)_{i,\text{obs}} \cdot \frac{\Delta x_i \times \mathcal{L}_{\text{int}}}{CF_i} \quad (4.17)$$

- μ_i (signal strength):

$$s_i = \mu_i \cdot \frac{(d\sigma/dx)_{i,\text{theory}} \times \Delta x_i \times \mathcal{L}_{\text{int}}}{CF_i} \quad (4.18)$$

where CF_i is the correction factor, Δx_i is the bin width, and $(d\sigma/dx)_{i,\text{theory}}$ is a theory prediction (all in the i -th bin).

The profile likelihood $\hat{L}(\psi)$ is used to extract the signal yields by fitting the observed distributions. It is defined as

$$\hat{L}(\psi) = \sup_{\lambda} L(\psi, \lambda) = L(\psi, \hat{\lambda}(\psi)) \quad (4.19)$$

where ψ are the parameters of interest (POIs), λ are the profiled nuisance parameters (NPs) and $\hat{\lambda}(\psi)$ is the maximum likelihood estimation of λ when

ψ is considered fixed.

A RooFit[49] based work-space using HistFactory [50] has been defined including all relevant NP's associated to the sources of systematic uncertainties of relevant parameters, namely the backgrounds, the integrated luminosity and the correction factors. NPs reflects the normalization uncertainties and shape uncertainties that are correlated across bins.

The extraction of the parameter of interest such as the cross sections (referred to as POIs) and of their errors is then obtained by the minimization of the negative logarithm of the profile likelihood, multiplied by a factor of 2 (2NLL) obtained by fitting the observed distributions.

For each parameter of interest, a scan of the 2NLL is performed while profiling all other parameters, i.e. they are fitted to the value that minimize the 2NLL for each value of the POI under study.

This method is based on the asymptotic assumption that states that such a statistical observable (2NLL) behaves as a χ^2 with n degrees of freedom, therefore, as one is only interested in changes in the value of the 2NLL it is useful to define the $\Delta 2\text{NLL}$ as the difference in 2NLL between a given point and the global minimum of the 2NLL.

Figure 4.24 shows the $\Delta 2\text{NLL}$ as a function of $N_{sig,i}^{reco}$ for the p_T distribution using the Asimov data set ⁵ without including systematic uncertainties in each bin. The variation of the 2NLL between its minimum and the $\Delta 2\text{NLL} = 1$ point can be used to estimate the uncertainty of the measurement at 68% CL, relying on the assumption that this statistical observable 2NLL behaves as a χ^2 distribution with one degree of freedom. Checks on the asymptotic behaviour of the likelihood have been performed (Section 4.5).

4.4 Systematic uncertainties

The systematic sources of uncertainties can be divided into two categories based on their impact on the analysis: those that primarily affect the predicted yields and those that primarily affect the shapes of the observables of interest in the signal region.

Systematics can arise from several sources. Concerning predictions from the simulation, mismodeling of reconstruction level observables used in the event selection generally leads to differing selection efficiencies between the simulation and data, resulting in possible biases in the measurements. For data-driven predictions such as the reducible background estimation, uncertainties can arise from limited statistics and/or uncertainty in the composition of a data control region.

⁵A data set in which all observed quantities are set equal to their expected values.

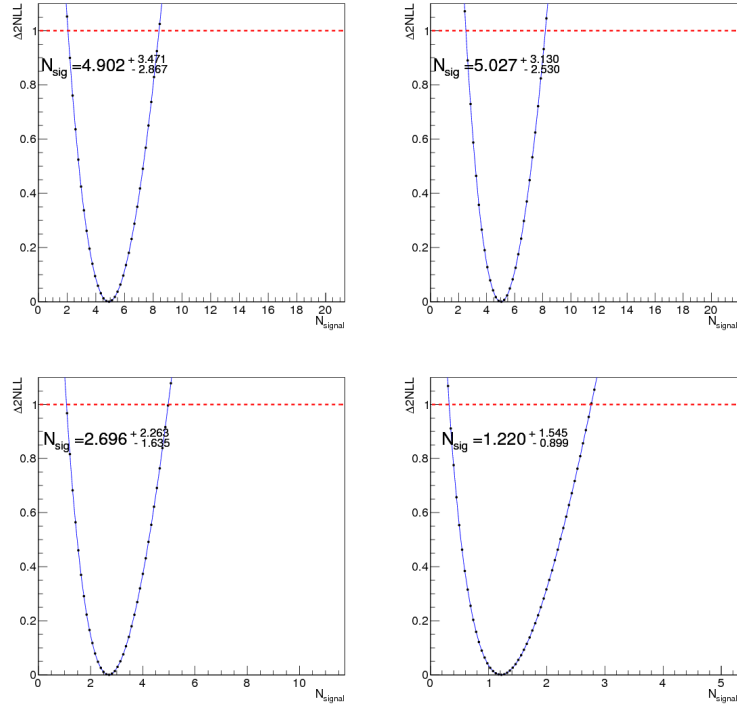


Figure 4.24: Scans of $\Delta 2\text{NLL}$ using Asimov data set for $N_{\text{sig},i}^{\text{reco}}$ in each bin of the p_T distribution.

4.4.1 Systematic uncertainties on the Inclusive cross section measurement

The systematic uncertainties in the **counting method** follow the same prescription used in the differential measurements with the exception that there are no shape systematic uncertainties, while for the **fit method**, the systematic uncertainties on the signal strength extraction are composed by the luminosity uncertainty ($\Delta\mathcal{L}_{int} = 2.8\%$), lepton efficiency uncertainties and theory uncertainties. It is used to normalize both the irreducible background and the signal yield predictions because both are taken from the simulation. It also factors directly into the calculation of the observed cross sections. Systematic uncertainties affecting the signal and background yields are evaluated by computing the difference between the nominal event yield and those obtained after applying a systematic variation to the simulated events. For systematic variations which affect individual leptons in an event, the uncertainties between leptons are treated as correlated in order to produce more conservative systematic uncertainties.

Table 4.12 summarizes the impact of the mentioned systematics on the signal yields.

Source of uncertainty	4μ	$2e2\mu$	$2\mu2e$	$4e$	combined
Electron reconstruction and identification efficiency	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	< 0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiency	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_S uncertainty					6.0%
$H \rightarrow ZZ^*$ branching ratio uncertainty					4.0%

Table 4.12: The expected impact of the systematic uncertainties on the signal yield that enter in the cross section measurement, derived from simulation, for $m_H = 125$ GeV, are summarized for each of the four final states for the $20.3fb^{-1}$ at $\sqrt{s} = 8$ TeV. The symbol – signifies that the systematic uncertainty does not contribute to a particular final state. The last three systematic uncertainties apply equally to all final states. All uncertainties have been symmetrized.

4.4.2 Systematic uncertainties for the differential cross section measurements

Systematic uncertainties in the differential cross section measurements can be categorized according to where they enter the cross section calculation:

- uncertainties in the observed number of signal events after background

subtraction (N_{sig}), which is directly related to uncertainties in the background predictions

- uncertainties on the correction factors (CFs), consisting of experimental and model dependence uncertainties
- uncertainties on the integrated luminosity $\mathcal{L}_{int}$
- uncertainties on the theoretical differential cross section predictions $(d\sigma/dx)_{theory}$ (which do not affect the measured cross sections)

Table 4.13 shows an overview of the systematic uncertainties considered in the differential cross section measurement, and Table 4.14 shows the resulting relative uncertainties. The ranges indicate the maximum and minimum relative uncertainty over all variables and bins.

Systematic source	N_{reco}^{sig}	CF	$\mathcal{L}_{int}$	$(d\sigma/dx)_{theory}$
Luminosity	✓		✓	
Experim. uncert. leptons/jet	✓	✓		
Irreducible background estimate (normalization)	✓			
Reducible background estimate (normalization/shape)	✓			
PDF/Scale+ α_S	✓	✓		✓
Unfolding model dependence		✓		
Higgs mass uncertainty		✓		✓

Table 4.13: Overview of the systematic uncertainties considered in the fiducial cross section measurements.

4.4.2.1 Systematic uncertainties due to the extraction of the signal yield

The uncertainties on N_{reco}^{sig} arise from several sources which affect the normalizations and reconstructed shapes of the backgrounds. The systematic uncertainties associated with lepton reconstruction, identification, and trigger efficiencies for the irreducible background are discussed in this section.

Luminosity systematic uncertainties

The total luminosity is taken to be $20.3 \pm 0.6 \text{ fb}^{-1}$ (corresponding to $\pm 2.8\%$). The corresponding uncertainty is propagated in a correlated way to the irreducible background that is evaluated from the MC predictions and to the cross-section unfolding.

Systematic Uncertainties (%)	
<i>Background</i>	
Luminosity	1.4–2.3
Reducible background	1.6–34
Experimental, leptons	1.3–2.3
PDF/scale	3.0–24
<i>Correction factors/conversion to σ</i>	
Luminosity	2.8
Experimental, leptons	2.1–2.6
Experimental, jets	2.7–13
Production process	0.1–15
Higgs boson mass	0.4–2.7

Table 4.14: Summary of the systematic uncertainties. The ranges indicate the dependence on variables and bins.

Lepton related systematic uncertainties

Systematic uncertainties have been evaluated for differences in lepton reconstruction, identification, and trigger efficiencies between the simulation and data for the irreducible background.

The systematic uncertainties on the irreducible background yield are evaluated by varying the lepton efficiency by $\pm 1\sigma$ and systematic variations are treated as fully correlated between same flavor leptons.

Tables 4.15 and 4.16 show the impact of the lepton systematic uncertainties on the irreducible background yield (shown here for the $qqZZ$ sample). The different efficiency uncertainties for trigger, reconstruction and identification have been added up in quadrature.

Variable	Bin0	Bin1	Bin2	Bin3	Bin4
$p_{T,H}$	2.43	2.44	2.35	2.19	0.00
$ y_H $	2.53	2.53	2.52	2.43	2.20
$ \cos(\theta^*) $	2.29	2.33	2.42	2.42	2.63
m_{34}	2.45	2.50	2.27	1.97	0.00
Incl	2.42	0.00	0.00	0.00	0.00

Table 4.15: Electron systematic uncertainties (in %) on the irreducible $qqZZ$ background yield.

Systematic uncertainties on the data-driven extraction of the reducible background

As for the estimation of the reducible background yields, the associated shapes are also obtained separately for the muon sub-leading channels and

Variable	Bin0	Bin1	Bin2	Bin3	Bin4
$p_{T,H}$	1.38	1.36	1.34	1.25	0.00
$ y_H $	1.30	1.29	1.30	1.35	1.59
$ \cos(\theta^*) $	1.30	1.31	1.35	1.42	1.44
m_{34}	1.49	1.34	1.12	1.11	0.00
Incl	1.37	0.00	0.00	0.00	0.00

Table 4.16: Muon systematic uncertainties (in %) on the irreducible $qqZZ$ background yield.

for the electron sub-leading channels.

Concerning the $\ell\ell + \mu\mu$ reducible background the nominal shapes are taken from Z +jets and $t\bar{t}$ MC simulation in the signal region; two systematic variations are assigned to these shapes, obtained by varying some of the cuts used in the selection of the sub-leading leptons ⁶:

- upper variation: $(\Sigma_{p_T}/p_T)_{\Delta R} < 0.1$ and $d_0 < 3$
- lower variation: $(\Sigma_{p_T}/p_T)_{\Delta R} < 0.3$ and $d_0 < 4.5$

The three curves have been all normalized to the final estimation to get the shape uncertainties (the systematic error associated to this normalization factor is also considered among the uncertainties).

For the $\ell\ell+ee$ channels the shapes are instead taken from data control regions and extrapolated to the signal regions by applying proper transfer factors. For the nominal shapes, the $3\ell + X$ Control Region is used; two systematic variations are again assigned to these shapes, obtained by using different data control regions and estimation methods. The three curves have been all normalized to the $3\ell + X$ final estimation (in the full mass range), and the associated systematic error have been also taken into account.

Figures 4.25 and 4.26 shows the smoothed shapes for all the variables used in the differential cross section measurements; the event counts in the $m_{4\ell}$ window $[118, 129]$ GeV are shown.

Theoretical systematic uncertainties due to PDF and higher orders in QCD for the $qqZZ$ background

Systematic uncertainties have been also assigned to account for uncertainties in the theoretical predictions for the irreducible ZZ background. These arise due to uncertainties in Parton Distribution Function (PDF) used at the generator level and also due to the choice of QCD factorization and renormalization scales, related to the estimate of the missing higher order QCD computations.

The main ZZ production mechanism in the mass region selected in this

⁶ d_0 is the impact parameter in the bending plane with respect to the primary vertex.

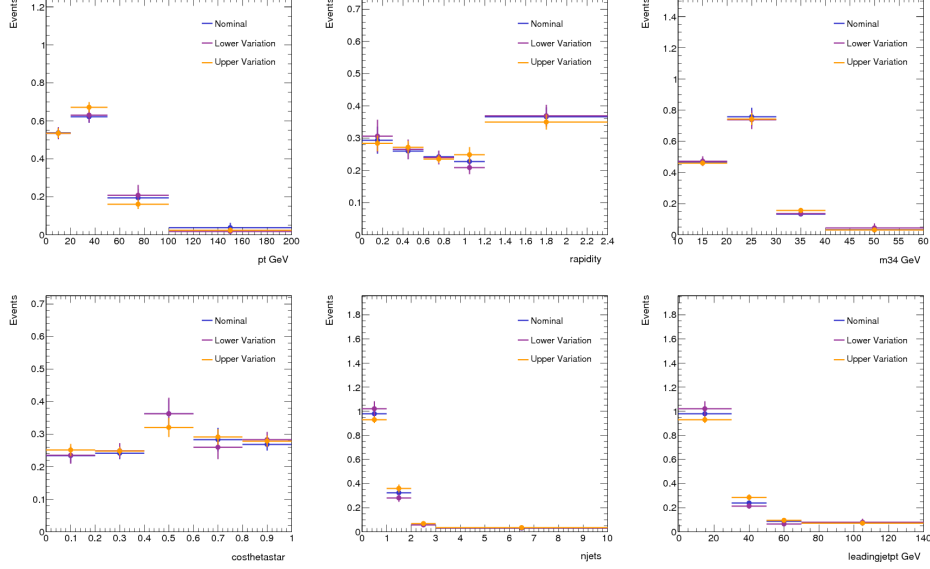


Figure 4.25: Reducible background shapes for the $\ell\ell + \mu\mu$ channels in the $m_{4\ell}$ window $[118,129]$ GeV. All variables used in the differential cross section measurement are shown.

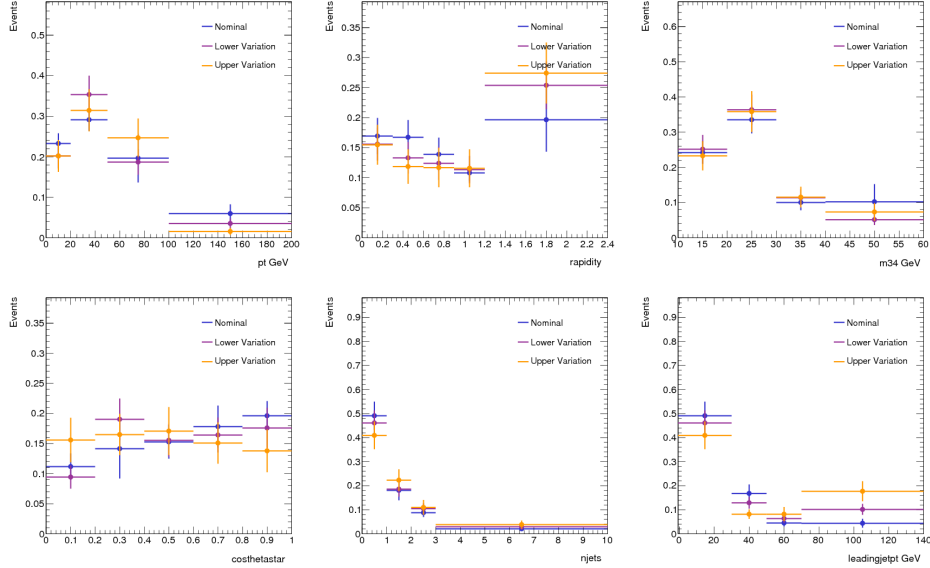


Figure 4.26: Reducible background shapes for the $\ell\ell + ee$ channels in the $m_{4\ell}$ range $[118,129]$ GeV. All variables used in the differential cross section measurement are shown.

analysis is expected to be via qq annihilation. The normalization for this background is taken from theory prediction with an associated uncertainty of 4%. In addition a small contribution from the gluon-gluon annihilation process is also added normalized to theory predictions with a normalization uncertainty of 30%.

The gluon-gluon production contribution is expected to be very small in the signal mass window (at the level of $< 0.5\%$). The interference between the $gg \rightarrow ZZ^*$ and the ggH signal is expected to be below 1% in the signal mass window [46] and is neglected in this analysis.

Additional shape uncertainties can also arise due to the PDF and QCD scale uncertainties. For the Higgs boson kinematic variables, these uncertainties have been evaluated by repeating the background estimates with different choices of PDF and QCD scales: for each kinematic variable, event weights have been derived by taking the ratio between the variation and the nominal differential distribution at truth level. The weights have been applied to the reconstructed events and the systematic uncertainty for each bin is defined as the maximum variation (up/down) with respect to the nominal value.

For the jet variables, an alternative method has been used (described in the next paragraph).

To evaluate the QCD scale uncertainties, 1 million events have been generated using POWHEG with 7 different configurations (*diamond scan*), where the renormalization and factorization scales were varied with this rule:

$$\frac{1}{4} < \frac{\mu_F}{\mu_R} < 4 \quad (4.20)$$

where $\mu_F = \mu_R = m_Z$ is the nominal value and the points $\mu_F = 0.5, 2 * m_Z$, $\mu_R = 0.5, 2 * m_Z$ are the variations up/down for each scale. Table 4.17 reports the derived systematics bin-by-bin for the kinematic variables.

The PDF uncertainties are evaluated with an envelope among 50 variations of the CT10 PDF set and the maximum variation with MSTW and NNPDF. First, the eigenvector sets included with the CT10 PDF set are used to derive one set of variations; the second set of variations is created by using the MSTW2008 PDF set and the NNPD 2.3 PDF set. The errors (up/down) for each bin are evaluated with CTEQ master formula [51]:

$$\Delta X^+ = \sqrt{\sum_{i=1}^N [\max(X_i^+ - X_0, X_i^- - X_0, 0)^2]} \quad (4.21)$$

$$\Delta X^- = \sqrt{\sum_{i=1}^N [\max(X_0 - X_i^+, X_0 - X_i^-, 0)^2]} \quad (4.22)$$

ΔX^+ and ΔX^- are summed in quadrature with the maximum variation of NNPDF and MSTW.

Table 4.18 reports the derived systematics bin-by-bin for the kinematic variables.

variable	bin	Δ^+	Δ^-
$p_{T,H}$	1	-2.7%	+1.2%
	2	+3.8%	-3.1%
	3	+5.6%	-2.0%
	4	+7.8%	+0.04%
$ y_H $	1	-0.09%	+0.05%
	2	-0.11%	+0.14%
	3	+0.17%	-0.18%
	4	-0.23%	+0.22%
	5	+0.14%	-0.12%

Table 4.17: Shape systematic uncertainties bin-per-bin for the irreducible background due to renormalization and factorization scale systematic uncertainties for the $p_{T,H}$ and $|y_H|$ distributions.

variable	bin	Δ^+	Δ^-
$p_{T,H}$	1	-2.0%	+2.2%
	2	+3.1%	-3.8%
	3	+3.1%	-3.9%
	4	+3.5%	-3.6%
$ y_H $	1	-0.05%	+0.07%
	2	-0.13%	+0.13%
	3	+0.17%	-0.17%
	4	-0.22%	+0.22%
	5	+0.13%	-0.13%

Table 4.18: Shape systematic uncertainties bin-per-bin for the irreducible background due to PDF systematic uncertainties for the $p_{T,H}$ and $|y_H|$ distributions.

4.4.2.1.1 Jet related systematic uncertainties in the ZZ background

Systematic uncertainties are assigned to account for both theory mis-modeling of higher order QCD-related processes and experimental mis-modeling of the jet detector response.

As the event selection does not depend on the jet selection, this mis-modeling will not affect the ZZ background normalization, however, both sources of mis-modeling can affect the background shape predictions of the N_{jets} and $p_{T,jet}$ distributions.

As already mentioned, the dominant irreducible background, $qq \rightarrow ZZ$, is modeled using Powheg, which is a NLO MC generator (therefore the first jet is LO, while the second comes from the parton shower). Due to the use of a fixed order calculation, one does not expect the shape of the N_{jets} and $p_{T,jet}$ distributions to necessarily be well modeled by the simulation, therefore, a data-driven means of evaluating this systematic uncertainty has been implemented. The high mass control region ($m_{4\ell} > 190$) GeV consists almost entirely of irreducible background which provides a suitable control region for evaluating the mis-modeling of the jet distributions.

The systematic uncertainty is then evaluated as the larger of:

- the data-MC difference
- the statistical uncertainty on the data in the control region after normalizing the MC estimate to the observed data yield

This systematic uncertainty should account for both theory and experimental uncertainties in the mis-modeling of the jet distributions. Table 4.19 shows the derived shape uncertainties for the jet variables.

Variable	Systematic Uncertainty (%)			
	Bin 1	Bin 2	Bin 3	Bin 4
N_{jets}	7.9	13.0	25.1	48.9
$p_{T,jet}$	7.9	18.9	22.1	22.0

Table 4.19: Systematic uncertainties on the ZZ background shape derived using the data-MC comparison in the high mass control region ($m_{4\ell} > 190$ GeV).

4.4.2.2 Systematic uncertainties affecting the Correction Factors (CFs)

Luminosity systematic uncertainty

As described in Sec. 4.4.2.1, the luminosity systematic uncertainty ($\pm 2.8\%$) is

propagated in a correlated way to the irreducible background evaluated from the MC predictions and to the unfolding, where it is used when converting the estimated unfolded signal yield into a fiducial cross-section.

Lepton related systematic uncertainties

The same lepton systematic uncertainties are evaluated for the signal correction factor as described in Sec. 4.4.2.1 for the ZZ background. All systematic uncertainties were evaluated using the SM prediction with $M_H = 125$ GeV. Tables 4.20 and 4.21 show a summary of the lepton systematics: the trigger, reconstruction and identification contributions have been added in quadrature.

Variable	Bin0	Bin1	Bin2	Bin3	Bin4
$p_{T,H}$	2.25	2.17	2.06	1.75	0.00
$ y_H $	2.16	2.19	2.16	2.16	1.90
$ \cos(\theta^*) $	2.11	2.14	2.08	2.07	2.21
m_{34}	2.30	2.26	2.00	1.87	0.00
N_{jets}	2.22	2.10	1.91	1.72	0.00
$p_{T,jet}$	2.22	2.11	2.01	1.96	0.00
Incl	2.12	0.00	0.00	0.00	0.00

Table 4.20: Electron systematic uncertainties on the correction factor (in %) as derived using the $m_H = 125$ GeV signal samples, bin-by-bin. The different contributions due to trigger, reconstruction and identification were added up quadratically.

Variable	Bin0	Bin1	Bin2	Bin3	Bin4
$p_{T,H}$	1.21	1.20	1.19	1.09	0.00
$ y_H $	1.16	1.12	1.15	1.19	1.39
$ \cos(\theta^*) $	1.15	1.17	1.20	1.21	1.20
m_{34}	1.28	1.24	1.10	1.01	0.00
N_{jets}	1.20	1.18	1.15	1.16	0.00
$p_{T,jet}$	1.20	1.21	1.20	1.13	0.00
Incl	1.19	0.00	0.00	0.00	0.00

Table 4.21: Muon systematic uncertainties on the correction factor (in %) as derived using the $m_H = 125$ GeV signal samples, bin-by-bin. The different contributions due to trigger and reconstruction were added up quadratically.

Jet Related Systematic Uncertainties

Systematic uncertainties are assigned for differences in the jet resolution and energy scales between the simulation and the data for the correction factors

exclusively for jet-related variables. Those are evaluated by applying a total of 23 variations up and down for the jet energy scale, one variation for the jet energy resolution, and one variation on the JVF cut: the differences in the bin-by-bin yields are assigned as a systematic uncertainty for each variation. All variations are treated as uncorrelated.

Figure 4.27 shows the derived jet-related systematic uncertainties, grouped in categories. The largest systematic is due to uncertainty in the jet flavor composition.

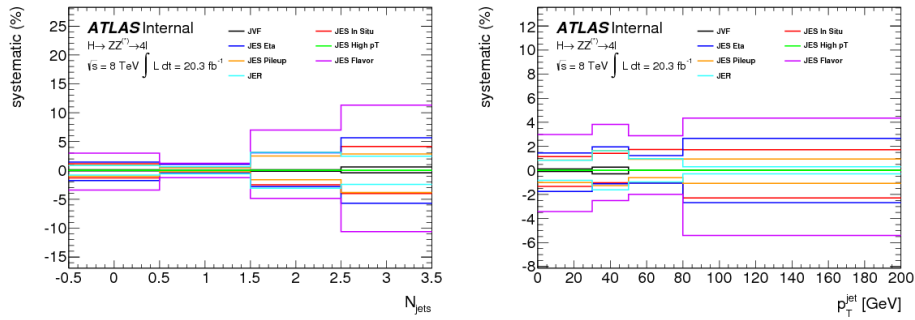


Figure 4.27: Systematic uncertainties on the signal correction factors due to the jet energy scale and resolution uncertainties and JVF cut efficiency uncertainty derived using the SM prediction with $M_H = 125$ GeV.

Dependence on the signal model

The correction factors method can introduce biases depending on the model used to derive them and, as already seen CFs depend on the signal production mode.

To evaluate the potential size of this bias and assign a corresponding systematic uncertainty, the correction factors have been calculated for a number of signal models by varying the signal production mode composition. Additional checks with non-SM spin models samples have been also performed to test the model dependency of the CFs: the variations on the signal model were found to be negligible.

The correction factors have been computed (for $m_H = 125.4$ GeV) for each of the different SM production mechanisms (gluon-fusion, VBF, VH and ttH associated production) as shown in Figure 4.21. Note that the correction factors for the different production modes differ by less than 10% with the exception of the ttH production mode, where large differences can be seen, especially for the jet-related variables.

The final correction factors are calculated using the SM prediction for the composition of the signal production modes. A systematic uncertainty due to this assumption on the composition is evaluated by varying the composi-

tion within the current experimental constraints on the signal strengths for the various production modes. Figure 4.28 shows the ATLAS constraints on the signal strengths (up to 2014) in the various production modes [48]. Furthermore, a limit on the $t\bar{t}H$ production mode has been produced which sets the observed 95% confidence-level upper limit at 4.1 times the SM cross section.

Therefore, the following variations are chosen to estimate the signal composition systematic uncertainty:

- Vary the VBF contribution by a factor of 0.5 times and 2 times of the SM prediction.
- Vary the WH contribution by a factor of 0.5 times and 2 times of the SM prediction.
- Vary the ZH contribution by a factor of 0.5 times and 2 times of the SM prediction.
- Vary the $t\bar{t}H$ contribution by a factor of 0 times and 5 times of the SM prediction.

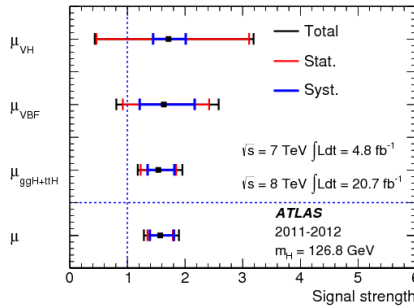


Figure 4.28: ATLAS measurements of the signal strength μ in the various Higgs production modes. This figure does not contain the very latest results (up to 2014), but changes in later iterations are small.

The results of this procedure are shown in Table 4.22. The systematic uncertainties ranges between 0.3 up to 4.3%: that results in an uncertainty of 0.3% on the inclusive correction factor.

Dependence on the Higgs mass

The experimental uncertainty in m_H , at the level of 0.5 GeV (up to 2014), results in an uncertainty on the correction factors since they are derived using a fixed value of $m_H = 125 \text{ GeV}$. As already seen, the inclusive fiducial efficiency does not strongly depend on the Higgs mass in the range

Variable	Systematic Uncertainty (%)				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
p_T	0.05	0.25	0.98	2.64	0.00
$ y $	0.76	0.69	0.66	0.56	0.55
m_{34}	0.73	0.65	0.64	0.51	0.00
$ \cos\theta^* $	0.66	0.67	0.60	0.61	0.70
N_{jets}	0.22	1.17	0.91	15.39	0.00
$p_{T,jet}$	0.22	1.30	0.78	2.83	0.00

Table 4.22: Systematic uncertainties on the correction factors derived by varying the signal mode composition with the $m_H = 125$ GeV signal samples.

[123,127] GeV. Applying the mass window cut slightly increases this dependence, as seen in Figure 4.7.

To evaluate this uncertainty, CFs have been derived using the signal samples with $m_H = 124, 125, 126$ GeV and for each bin the largest variations has been taken as the systematic uncertainty.

The results of this procedure for all variables are shown in Table 4.23. The systematic on the inclusive correction factor is found to be 1.7%.

Variable	Systematic Uncertainty (%)				
	Bin0	Bin1	Bin2	Bin3	Bin4
p_T	1.07	2.28	1.18	2.36	0.00
$ y $	1.30	2.97	3.53	1.15	4.00
m_{34}	1.20	0.78	2.31	2.39	0.00
$ \cos\theta^* $	2.12	3.14	1.69	1.09	2.79
N_{jets}	1.30	0.95	4.60	2.65	0.00
$p_{T,jet}$	1.30	2.49	2.05	1.57	0.00
Incl	1.67	0.00	0.00	0.00	0.00

Table 4.23: Systematic uncertainties on the correction factors derived by varying m_H from 124 GeV to 126 GeV.

Data-based $p_{T,H}$ Reweighting

In order to assess the effect of differences between the underlying spectra in the simulation and data, CFs have been calculated after applying a reweighting procedure to the simulation which causes the simulation to better describe the measured $p_{T,H}$ distributions. The event weights are derived

simply by dividing the observed cross section by the theory predictions:

$$w_i(p_{T,H}) = \frac{(d\sigma/dp_T)_{i,\text{obs}}}{(d\sigma/dp_T)_{i,\text{theory}}} \quad (4.23)$$

The correction factors are re-calculated after applying the weighting factor above to both the numerator and denominator of the correction factors; the relative variations in the correction factors after applying this procedure are shown in Table 4.24.

Variable	Systematic Uncertainty (%)				
	Bin0	Bin1	Bin2	Bin3	Bin4
Inclusive	0.22	-	-	-	-
p_T	4.55	2.49	0.51	0.089	-
$ y $	0.002	0.009	0.33	0.70	0.23
m_{34}	0.02	0.29	0.30	0.074	-
$ \cos\theta^* $	0.018	0.65	0.34	0.54	0.27
N_{jets}	0.72	0.35	0.98	0.55	-
$p_{T,jet}$	0.72	1.14	0.65	0.22	-

Table 4.24: Systematic uncertainties on the correction factors derived by re-weighting the simulated p_T spectrum to the observed spectrum.

4.4.2.3 Systematic uncertainties on generator level distributions

This section describes the determination of the systematic uncertainties of the generator level distributions that are compared to the unfolded cross-sections of our measurement.

The theoretical differential fiducial cross section predictions are subject to systematic uncertainties due to the choice of PDF and the choice of QCD renormalization and factorization scales. Each uncertainty has been evaluated by generating events with systematic variations in the PDF and scales. In order to isolate the shape differences between generator predictions, each prediction has been normalized to the CERN Yellow Report cross section times branching ratios for a 125.4 GeV Higgs [4].

Additional contributions from VBF (simulated with POWHEG+PYTHIA8), VH and $t\bar{t}H$ (PYTHIA8) processes are added to the estimate; PDF and QCD scale uncertainties are evaluated for VBF, while for VH and $t\bar{t}H$ the uncertainties are taken from the Yellow Report and assumed to be flat across the distributions.

Renormalization and factorization scale uncertainties are evaluated by varying μ_R and μ_F up (times 2) and down (times 0.5) from their nominal values, excluding $\mu_R/\mu_F = 4$ and 0.25 [4].

For the HRES2 calculation only, there are two additional resummation scales, $Q_1 = m_H/2$ and $Q_2 = m_b$ for the bottom quark contribution. These are varied up and down by factors of 2 while keeping μ_R/μ_F fixed at their nominal values (and vice-versa). The envelope of all variations is taken as the systematic uncertainty. The variation for the HRES2 prediction of the $p_{T,H}$ and $|y_H|$ distributions are shown in Figure 4.29. Two sets of variations

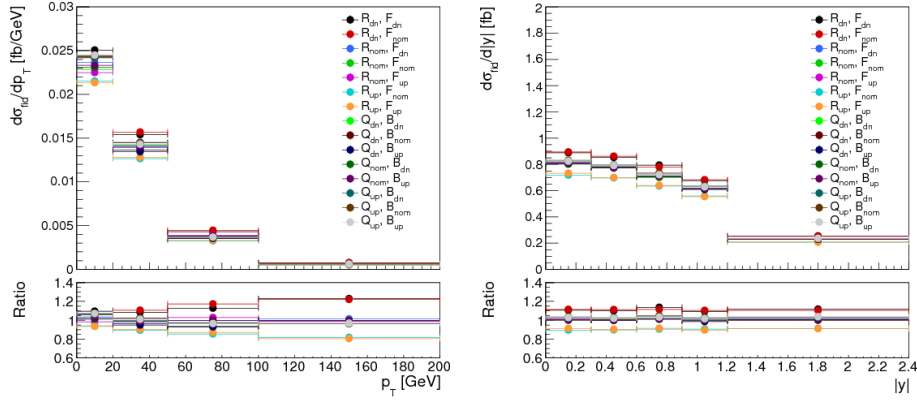


Figure 4.29: Comparisons of the 15 scale variations for a 125.4 GeV Higgs sample generated using HRES2. The ratio plots underneath are with respect to the nominal (R_{nom} , F_{nom}).

are performed for the choice of the PDF (the nominal is the CT10 PDF set). First, the eigenvector sets included with the CT10 PDF set are used to derive one set of variations; the second set of variations is created by using the MSTW2008 PDF set and the NNPD 2.3 PDF set.

The variations in the POWHEG prediction after changing PDF sets for the $p_{T,H}$ and $|y_H|$ is shown in Figure 4.30. For each set of variations, the systematic uncertainties are evaluated by taking the envelope of the difference between the variations and the nominal predictions; finally, the uncertainties from the eigenvector and PDF set choice are added in quadrature. To evaluate the QCD scale uncertainty in the N_{jets} distribution for Powheg and Minlo samples, the Stewart-Tackmann procedure is used to account for the additional perturbative uncertainty associated with a jet $p_{T,H}$ cut [52]. The Stewart-Tackmann scale uncertainty is used in place of the QCD scale uncertainty, and added in quadrature with the other uncertainties.

4.4.2.4 Ranking of the systematic errors for the differential cross section measurement

When the profile likelihood fit is performed, each nuisance parameter (NP) is profiled and the fitted values may differ from the nominal one. Its error may be constrained by the fit to the data; the profile likelihood fit then returns

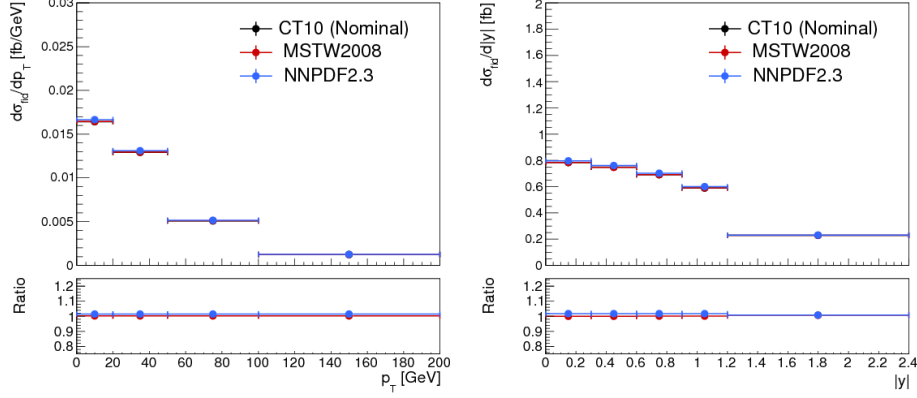


Figure 4.30: Comparisons of the nominal POWHEG generated sample (CT10) and the MSTW2008 and NNPDF 2.1 PDF variations, for a 125.4 GeV Higgs. The ratio plots underneath are with respect to the nominal (CT10).

the parameter of interest (the differential cross section in each bin). The Asimov data set is constructed from the nominal Monte Carlo expectation and the pulls in the Asimov data set are expected to be zero by construction. The size of the constraints on the nuisance parameters in the Asimov data set are statements about the power of the data to constrain the parameters. For each set of nuisance parameters, the resulting pulls and constraints from the fit to data are compared to those of the fit to the Asimov data to study correlations among the parameters. The NPs will be therefore zero in case of perfect Monte Carlo modeling of the signal and backgrounds, so any pull away from zero indicates that the fitting procedure has preferred to change the background model to agree with the data. The impact of each systematic uncertainty has been computed by obtaining the change in the POI value when the given uncertainty is shifted by $\pm 1\sigma$ from its best-fit value.

Ranking of the impact on the cross section in the first two bins of $p_{T,H}$ is shown as an example for the systematic uncertainties in the profile likelihood fit. The central value of the point for each nuisance parameter represents the pull of that parameter, and the value of the pull is given by the bottom axis.

4.5 Error calibration with toys

Pseudo-experiment studies (known as “toys”) have been performed to check the validity of the asymptotic assumption for the likelihood distribution. For each toy or pseudo-experiment, the observed number of events in each bin has been randomly drawn from a Poisson distribution with mean equal to the expected number of events (signal+background) for that bin. MI-

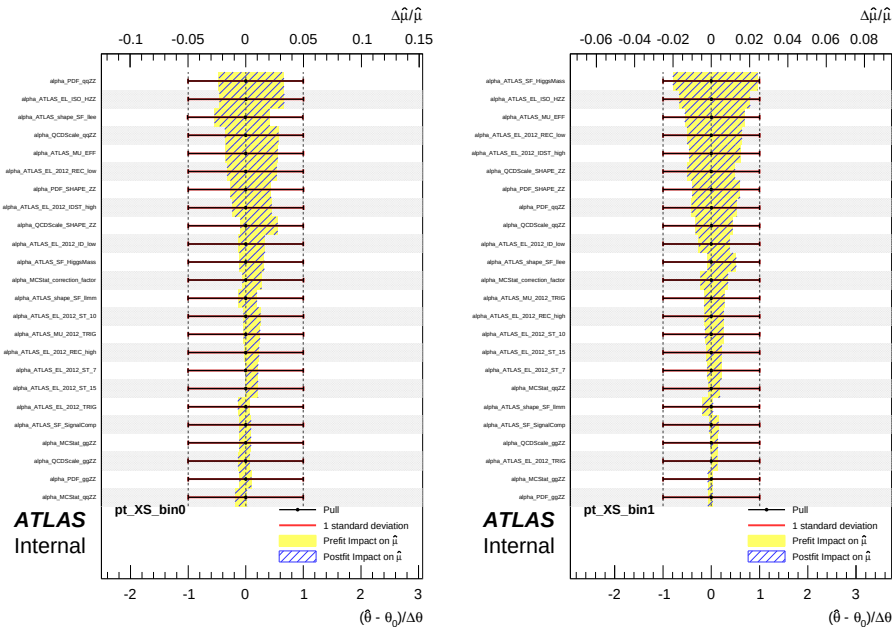


Figure 4.31: Ranking plots for the differential cross section in the first two $p_{T,H}$ bins.

NUIT is used for the minimization of the 2NLL function.

An amount of 100k toys have been produced for the $p_{T,H}$ distribution (reported here as an example) injecting the number of signal events for the SM expectation assuming $m_H = 125$ GeV. The results are shown for each $p_{T,H}$ bin in Figure 4.32. These studies use only a minimal set of systematic uncertainties composed by the luminosity and the largest experimental uncertainties; a small fraction ($\sim 0.6\%$) of toys with a fit convergence failure are not included in the results.

For all bins, the mean value of the parameters of interest agrees with the injected value within the 0.6% (negligible with respect to the expected statistical error), indicating that the method is unbiased.

It is interesting to observe that in bins with a small number of total expected events, the measured values are discretized due to the discrete nature of the observed number of events; smearing of these discrete values is observed due to the systematic constraints, which allow bin-to-bin correlations to modify the minimum of the 2NLL. The errors on the cross section measurements have therefore been computed also using pseudo-experiments, as they give a better estimation in case of a non asymptotic behaviour of the Likelihood. In order to do this, the aim is to find the cross section values corresponding to 1 sigma deviation from the value that minimizes the 2NLL; in an asymptotic regime this has to be equal to what obtained from the $\Delta 2NLL = 1$

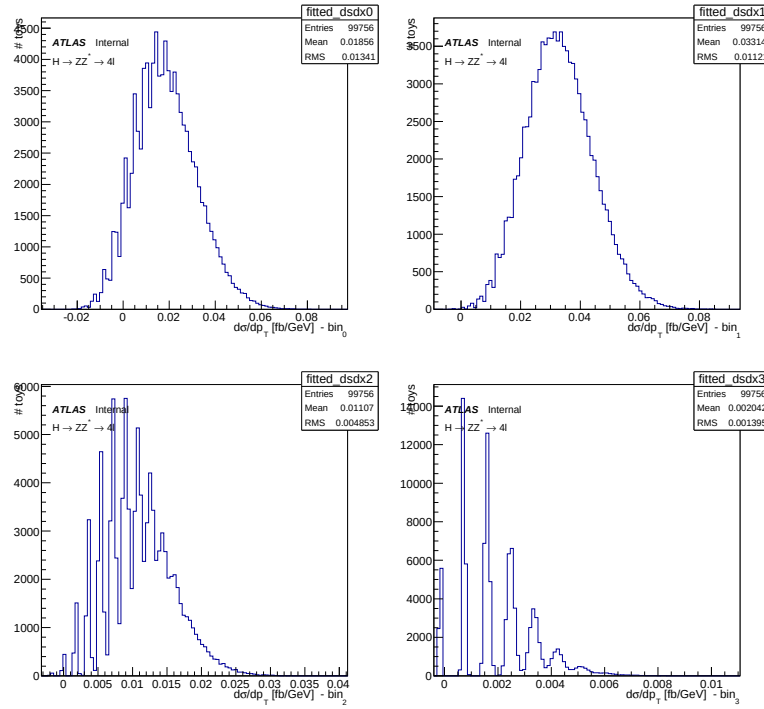


Figure 4.32: Distribution of fitted differential cross section per bin $((d\sigma/dx)_i)$ for 100k pseudo-experiments with the SM signal injected assuming $m_H = 125$ GeV, the spikes are due to a low statistical regime, where the fit becomes sensitive to the extraction of the single event. The mean of the distribution in each bin is consistent with the injected number of signal events.

(Figure 4.33). Due to the non-asymptotic behaviour of the Likelihood, the

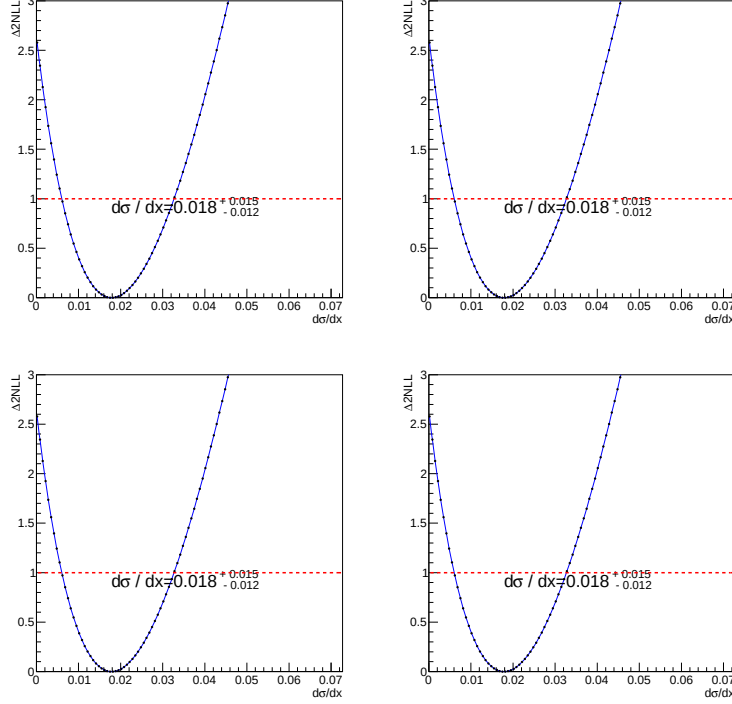


Figure 4.33: Scans of the 2NLL distribution of the cross section values in each bin of $p_{T,H}$.

q-test ($q = \Delta 2NLL$ ⁷) has been used to extract the compatibility of the measurements with theory prediction.

Toys have been generated at different cross section values, and fitted two times, once fixing the cross section under study to the value injected, once profiling it (each bin is taken into account separately).

The $\Delta 2NLL$ obtained as described before, behaves as a χ^2 distribution with 1 dof in the asymptotic limit. The idea, then, is to check the behaviour of this distribution, where the 1σ interval is given by the cross section injected

⁷The q test statistic is based on a ratio of profiled likelihoods [43]:

$$q = 2 \log \frac{\mathcal{L}(\hat{P}\hat{O}I, \hat{N}P)}{\mathcal{L}(\hat{P}\hat{O}I, \hat{N}P)}, \quad (4.24)$$

where $\mathcal{L}(\hat{P}\hat{O}I, \hat{N}P)$ is the maximum likelihood estimator, evaluated profiling all the parameters while $\mathcal{L}(\hat{P}\hat{O}I, \hat{N}P)$ is the value of the maximum likelihood estimator for a specific set of parameters (characterizing the hypothesis under investigation). The value of the test statistic is used to compare the different the probabilities of hypothesis and construct a likelihood scan over the parameter of interest.

in correspondence of the $\Delta 2NLL$ value at the 68% of the toys generated. As shown in Figures 4.34 and 4.35 (respectively for the $+$ and -1σ variation in the injected values of the cross sections), for the bins that are in a high statistics regime, the $\Delta 2NLL$ behaves like a χ^2 with 1 dof, while for the bins that suffer from low statistics, the $\Delta 2NLL$ does not follow a χ^2 with 1 dof.

The former are the cases in which the $\pm 1\sigma$ errors computed using toys give exactly the same results as in the scan of the $2NLL$; the latter shows that, in those cases, the errors compute with the toy studies are about 20% smaller with respect to those computed with the asymptotic assumption.

Table 4.25 compares the uncertainties of the $2NLL$ with those resulting from the RMS and the 68% confidence level interval using toys for the extraction of $d\sigma/dp_{T,H}$. The differences between the asymptotic ($\Delta 2NLL$) uncertainties and the uncertainties derived using toys range from 8-45%, with the majority being within 20%. Figure 4.36 shows the scan on the value of the

Bin, dir.	2NLL uncertainties	toy RMS	toy 68% C.L. interval
Bin 0, up	0.0153	0.0134	0.0132
Bin 0, down	0.0126	0.0134	0.0135
Bin 1, up	0.0093	0.0084	0.0086
Bin 1, down	0.0075	0.0084	0.0084
Bin 2, up	0.0041	0.0037	0.0034
Bin 2, down	0.0029	0.0037	0.0039
Bin 3, up	0.00136	0.00127	0.00093
Bin 3, down	0.00079	0.00126	0.00099

Table 4.25: Comparison of uncertainties from the $2NLL$ scan with the RMS and the 68% C.L. interval obtained with the toys for the extraction of $d\sigma/dp_T$.

cross sections near to the errors computed in the asymptotic assumption; the errors with toys are extrapolated from the value of the injected cross sections which correspond at the 68% of toys. Two cases are shown: the case of high statistics in which the errors computed using toys and using the likelihood scan perfectly agree, and the case in which the asymptotic assumption is not valid due to the low statistics regime, respectively the 3rd and the 4th bin in the $p_{T,H}$ differential cross section distribution.

4.5.1 Compatibility studies using toys

Since it has been demonstrated that the asymptotic approximation is not valid, toys have been used to estimate the final uncertainty on the measured cross-sections.

The idea is to use pseudo-experiments and to compute the $\Delta 2NLL$ between

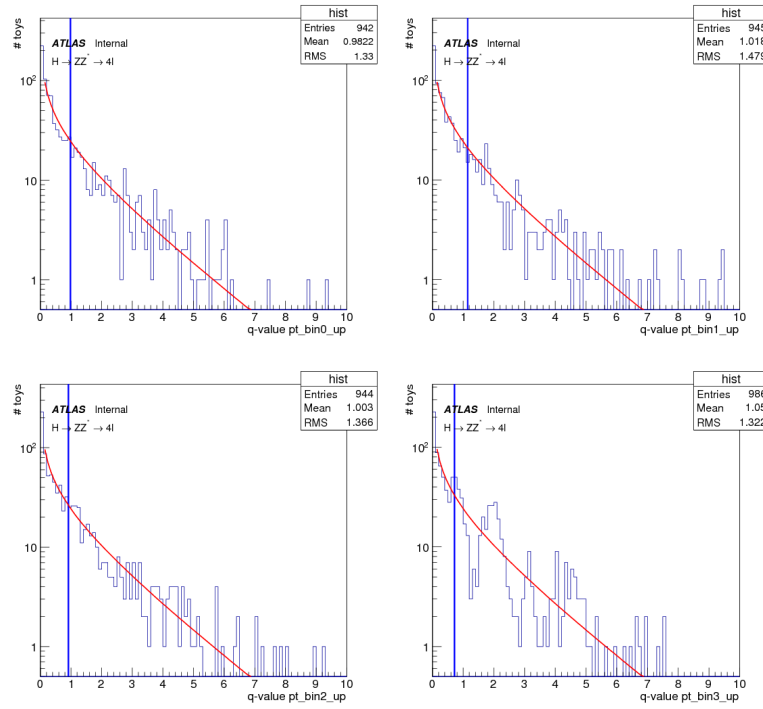


Figure 4.34: $\Delta 2NLL$ computed using pseudo experiments generated at the cross section values at $+1\sigma$ from the scan; in the asymptotic assumption the function should behave as a χ^2 with 1 dof (red line), while in blue the $\Delta 2NLL_{obs}$ is shown.

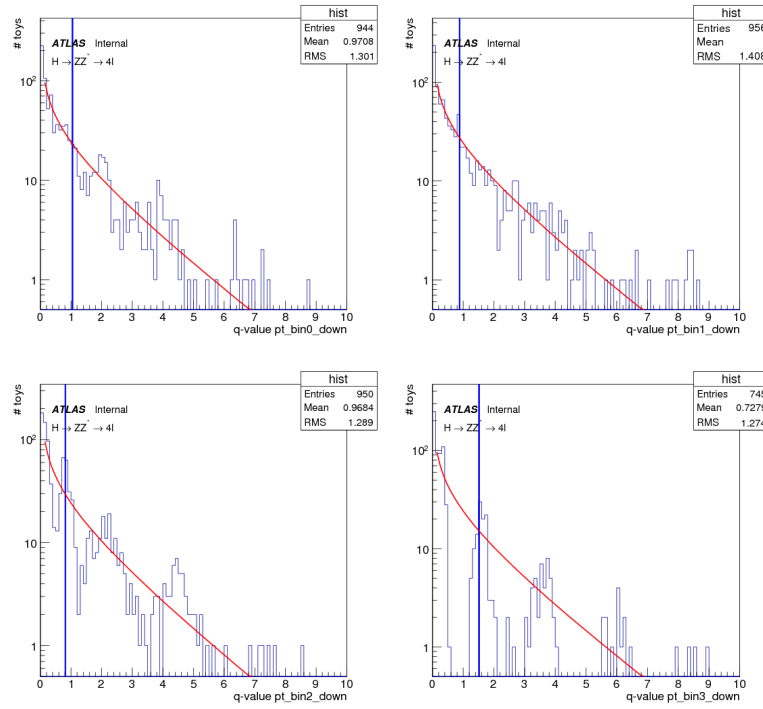


Figure 4.35: $\Delta 2NLL$ computed using pseudo experiments generated at the cross section values at -1σ from the scan; in the asymptotic assumption the function should behave as a χ^2 with 1 dof (red line), while in blue the $\Delta 2NLL_{obs}$ is shown.

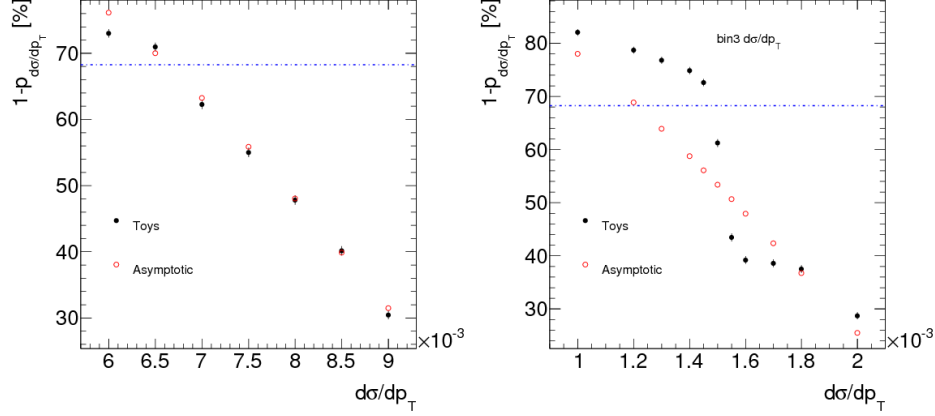


Figure 4.36: The scan on the value of the cross sections near to the errors computed in the asymptotic assumption are shown; the errors with toys are extrapolated from the value of the injected cross sections which correspond at the 68% of toys.

the Likelihood build with all the cross sections (all the bins are taken into account altogether) fixed to the theory computation values and with all the parameters of interest profiled. That distribution should behave as a χ^2 with N_{bins} dof (4 in case of $p_{T,H}$). In an asymptotic regime, the agreement would be quoted as the probability to observe such a $\Delta 2NLL_{obs}$ value, given the χ^2 distribution with N_{bins} dof; while for the toys studies, it is given from the fraction of toys whose $\Delta 2NLL$ is greater than the $\Delta 2NLL_{obs}$.

Checks have been made using HRes2.2 for the Higgs boson kinematics variables, MINLO and Powheg for the whole set as shown in Figure 4.37. Tables 4.26, 4.27 and 4.28, report the agreement with SM predictions both using the asymptotic assumption and the toys studies: no significant deviations from the SM-based theoretical predictions have been observed.

Variable	Agreement (asyp.)	Agreement (toys)
$p_{T,H}$	30%	$33 \pm 1\%$
$ y_H $	37%	$38 \pm 1\%$
$ \cos(\theta^*) $	44%	$48 \pm 1\%$
m_{34}	35%	$38 \pm 1\%$
N_{jets}	37%	$40 \pm 1\%$
$p_T^{jet,1}$	33%	$37 \pm 1\%$

Table 4.26: Compatibilities with Powheg computed using toys and compared to the asymptotic assumption. The errors are computed according to the Poisson statistics on the number of toys.

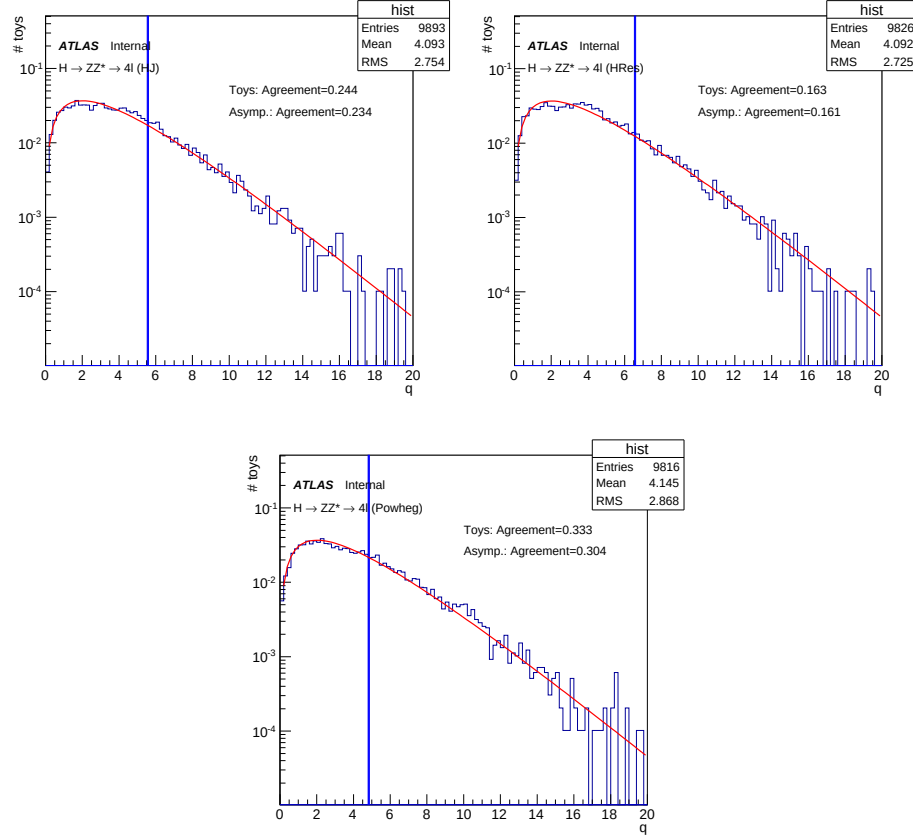


Figure 4.37: The q -test distribution built taking into account all the $p_{T,H}$ bins is shown together with the q_{obs} value obtained from data.

Variable	Agreement (asyp.)	Agreement (toys)
$p_{T,H}$	23%	$24 \pm 1\%$
$ y_H $	45%	$47 \pm 1\%$
$ \cos(\theta^*) $	56%	$59 \pm 1\%$
m_{34}	45%	$47 \pm 1\%$
N_{jets}	28%	$29 \pm 1\%$
$p_T^{jet,1}$	26%	$29 \pm 1\%$

Table 4.27: Compatibilities with MINLO HJ computed using toys and compared to the asymptotic assumption. The errors are computed according to the Poisson statistics on the number of toys.

Variable	Agreement (asyp.)	Agreement (toys)
$p_{T,H}$	16%	$16 \pm 1\%$
$ y_H $	36%	$37 \pm 1\%$

Table 4.28: Compatibilities with HRes2.2 computed using toys and compared to the asymptotic assumption. The errors are computed according to the Poisson statistics on the number of toys.

4.6 Fiducial cross-section results

As already stressed, fiducial cross sections are used to minimize the model dependence of the acceptance corrections due to extrapolation to phase space regions not covered by the detector; Correction Factors are then used to unfold the reco distribution to the truth one.

The results of the inclusive and differential cross section measurements are presented in this Section.

4.6.1 Inclusive results

4.6.1.1 Counting method results

The expected number of signal and background events and the observed number of events within the mass window are shown in Table 4.29.

A clear excess with respect to background is observed: the measured number of events in the signal region is $25.11^{+6.28}_{-5.39}(\text{stat})^{+0.57}_{-0.41}(\text{syst})$ events and the correction factor ($1/\epsilon_{fid}$) within the mass window is $1.796 \pm 0.007(\text{stat}) \pm 0.054(\text{syst})$.

The scan of the $\Delta 2\text{NLL}$ is shown in Figure 4.38 and the observed fiducial cross section is measured to be:

$$\sigma_{fid} \cdot BR = 2.21^{+0.56}_{-0.48}(\text{stat})^{+0.14}_{-0.10}(\text{syst}) \text{ fb}$$

20.3 fb ⁻¹ @ $\sqrt{s} = 8$ TeV, $118 < m_{4\ell} < 129$ GeV				
SM Signal	ZZ	Reducible	Total Background	Observed
14.1	6.7	2.4	9.0	34

Table 4.29: The expected number of signal and background events and the observed number of events within the mass window $[118, 129]$ GeV for 20.3 fb⁻¹@ $\sqrt{s} = 8$ TeV.

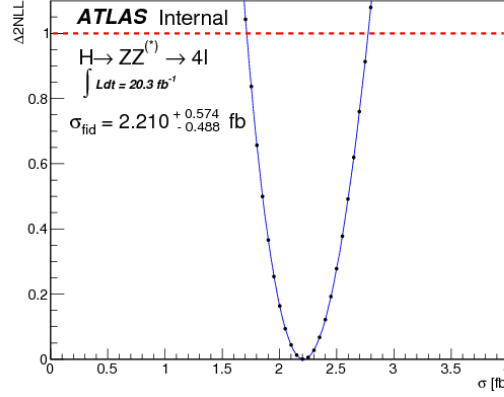


Figure 4.38: Scan of the $\Delta 2\text{NLL}$ in the fiducial cross section measurement using the counting method.

4.6.1.2 Fitting method results

The profile likelihood curve of the signal strength measurement resulting from the fit of the $m_{4\ell}$ distribution is shown in Figure 4.39. The systematic error is determined by taking the difference in quadrature between the 1σ interval computed by including statistical and systematic uncertainties, not including signal theory systematics. Multiplying the measured signal strength by the number of expected signal events at the fitted mass, the number of observed signal events within the the mass window [118, 129] GeV, N_{sig} , is $23.69^{+5.92(\text{stat})+0.60(\text{syst})}_{-5.26(\text{stat})-0.57(\text{syst})}$ events; the estimated correction factor ($1/\epsilon_{fid}$) is 1.81 ± 0.01 (stat) ± 0.05 (syst) and the measured luminosity is $20.3 \text{ fb}^{-1} \pm 2.8\%$.

Using Equation 4.3, the measured fiducial cross section times branching ratio is measured to be:

$$\sigma_{fid} \cdot BR = 2.11^{+0.53}_{-0.47}(\text{stat})^{+0.08}_{-0.08}(\text{syst}) \text{ fb}$$

The current theoretical prediction, including theoretical uncertainties from QCD scale, PDFs and branching ratio taken from the CERN Yellow Report[21] being:

$$\sigma_{fid} \cdot BR = 1.30 \pm 0.13 \text{ fb.}$$

4.6.2 Differential fiducial cross-section results

The predicted and observed number of events for the chosen variables are shown in Figure 4.40. The results show no evidence of deviations with respect to the SM expectations with accuracies at the level of 20 – 50%.

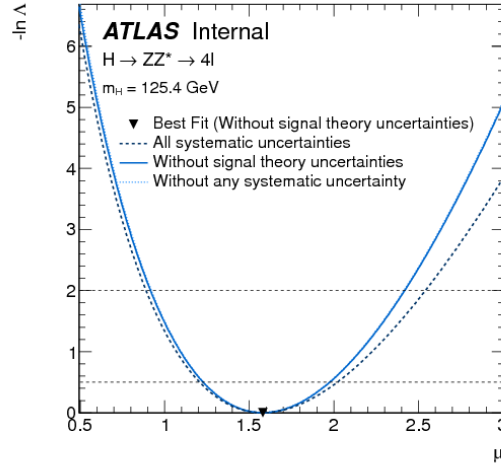


Figure 4.39: Profile likelihood curve for the signal strength measurement from the fit of the $m_{4\ell}$ distribution. The dashed dark blue curve includes all systematic uncertainties, the solid blue curve includes all systematic uncertainties except for signal theory systematics, and the dotted light blue curve includes only statistical uncertainties.

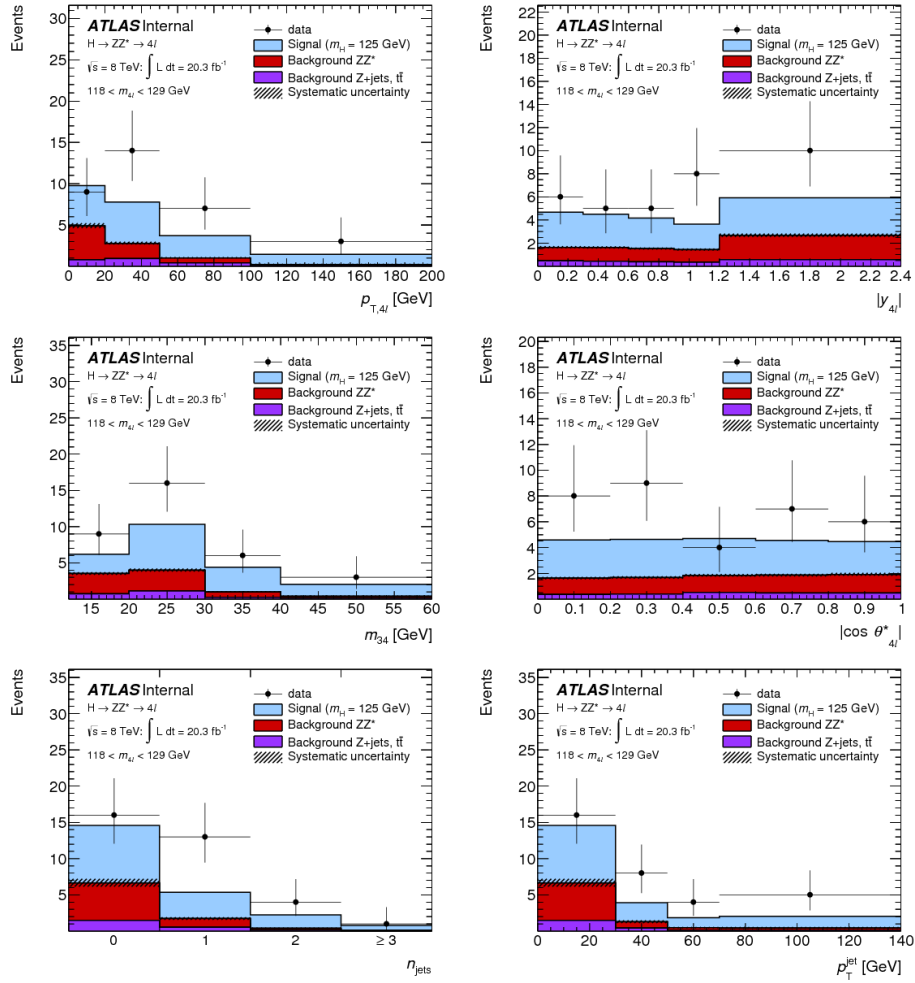


Figure 4.40: Background and signal predictions and data yields in the signal region ($118 < m_{4\ell} < 129$ GeV).

4.6.2.1 Resulting cross sections and signal strengths

The observed unfolded fiducial cross sections are finally shown in Figure 4.41 and in Table 4.30 together with the comparison to selected theory predictions.

A quantitative comparison of the results obtained with theory predictions is presented in the next Section.

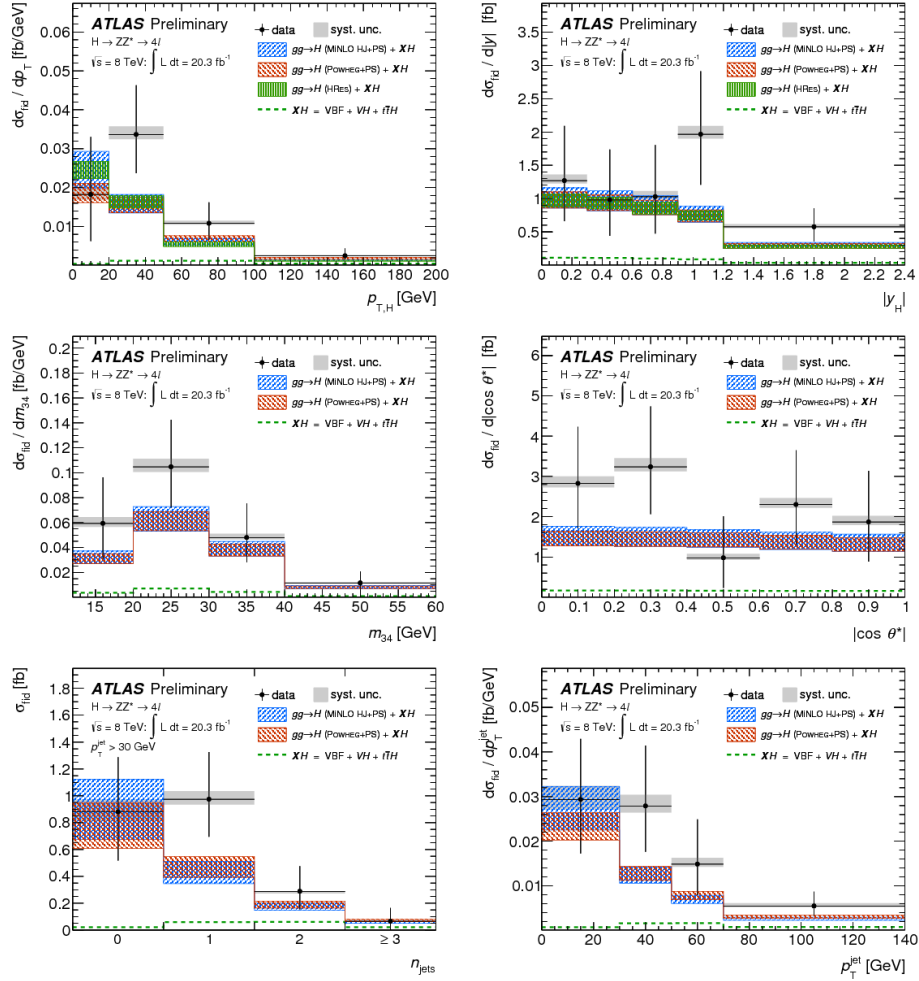


Figure 4.41: Measured differential cross sections ($d\sigma/dx$) in the 20.3 fb^{-1} of $\sqrt{s} = 8 \text{ TeV}$ dataset for all variables.

4.6.2.2 Comparison with different theory predictions

In order to quantify the agreement between the measured differential cross sections and the theory models, the following method has been used.

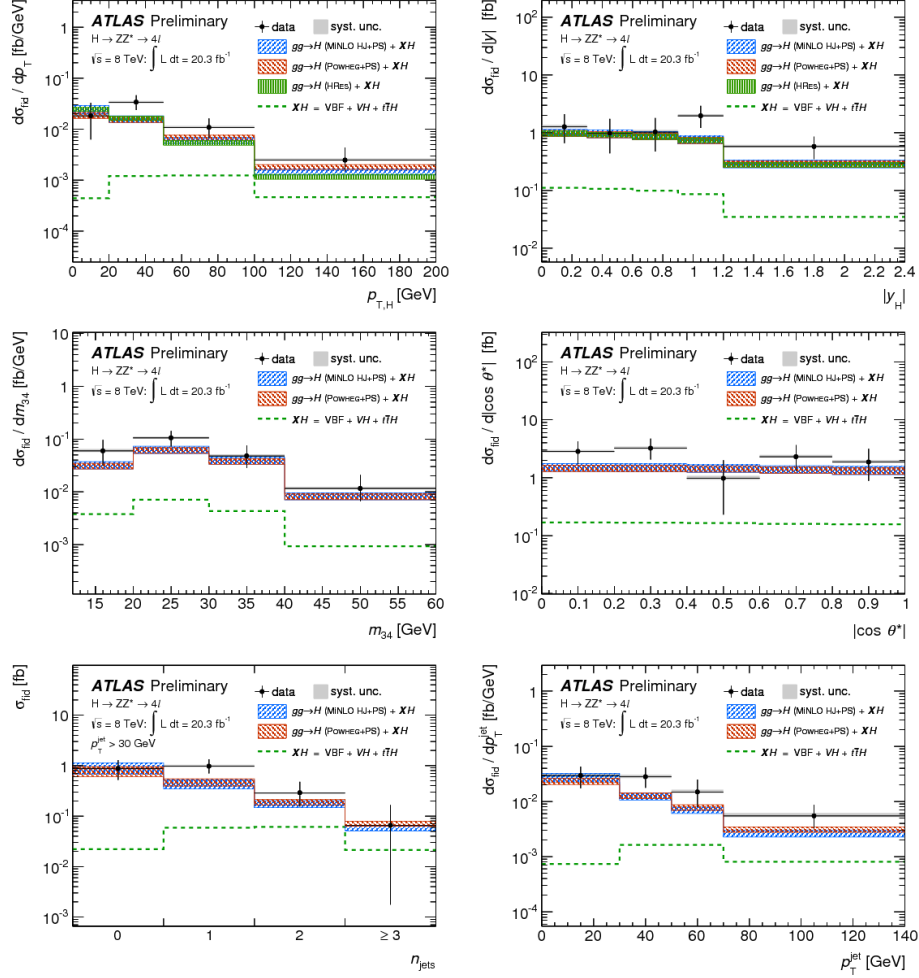


Figure 4.42: Measured differential cross sections ($d\sigma/dx$) in the 20.3 fb^{-1} of $\sqrt{s} = 8 \text{ TeV}$ dataset for all variables (log scale).

Variable	Unit	Bin 0	Bin 1	Bin 2	Bin 3	Bin 4
$p_{T,H}$	[fb/GeV]	$0.018^{+0.015}_{-0.012}$	$0.034^{+0.013}_{-0.010}$	$0.0108^{+0.0054}_{-0.0043}$	$0.0025^{+0.0019}_{-0.0010}$	-
$ y $	[fb]	$1.27^{+0.82}_{-0.61}$	$0.98^{+0.76}_{-0.54}$	$1.03^{+0.77}_{-0.56}$	$1.97^{+0.95}_{-0.76}$	$0.58^{+0.28}_{-0.23}$
m_{34}	[fb/GeV]	$0.059^{+0.037}_{-0.029}$	$0.105^{+0.038}_{-0.033}$	$0.048^{+0.027}_{-0.020}$	$0.0116^{+0.0092}_{-0.0050}$	-
$ \cos\theta^* $	[fb]	$2.8^{+1.4}_{-1.1}$	$3.2^{+1.5}_{-1.2}$	$0.98^{+1.03}_{-0.75}$	$2.3^{+1.3}_{-1.0}$	$1.87^{+1.27}_{-0.99}$
N_{jets}	[fb]	$0.88^{+0.41}_{-0.36}$	$0.97^{+0.35}_{-0.28}$	$0.29^{+0.19}_{-0.13}$	$0.065^{+0.099}_{-0.064}$	-
$p_{T,jet1}$	[fb/GeV]	$0.029^{+0.014}_{-0.012}$	$0.028^{+0.014}_{-0.010}$	$0.0148^{+0.0100}_{-0.0069}$	$0.0055^{+0.0032}_{-0.0023}$	-

Table 4.30: Observed differential cross sections for all variables in all bins. Both systematic and statistical uncertainties are included.

The profile likelihood defined to extract the differential cross section measurement has been modified in order to include scaling factors, μ_i defined as the ratio of the differential measured cross section with respect to that predicted by a given model.

In particular, the number of signal events that enters in the likelihood defined by Eq. 4.11 can be parametrized as:

$$s_i = \frac{\Delta x_i \times L \times (d\sigma/dx_i)_{Theory} \times \mu_i}{C_i} \quad (4.25)$$

where Δx_i is the bin size, L is the total integrated luminosity, $(d\sigma/dx_i)_{Theory}$ is the theory prediction for bin i , C_i are the Correction factors and μ_i are the parameters of interest fitted to the data.

With this definition the variation of twice the Negative Log-Likelihood (2NLL) between its minimum and the value where all $\mu_i = 1$, can be used to estimate the agreement between the data measured cross sections and the theory prediction since this quantity is expected to behave as a χ^2 with N_{bins} degrees of freedom.

The advantage of this methods is that nuisance parameters, associated with different systematics uncertainties, can be easily correlated between different bins, correction factors, backgrounds, and theory predictions.

All the observed cross section distributions as a function of the chosen interesting variables have been studied: results show no significant deviations with respect to the SM hypothesis. Table 4.31 shows the χ^2 probability with the SM hypothesis, which reflects the good agreement between the observed and predicted distributions.

Variable	χ^2 Compatibility (%)		
	Powheg	HRes2.0	MinLo
$p_{T,H}$	30	16	23
$ y $	37	36	45
m_{34}	48	-	60
$ \cos\theta^* $	35	-	45
N_{jets}	37	-	28
$p_{T,jet1}$	33	-	26

Table 4.31: Compatibility test with the SM hypothesis the Powheg, HRes2.0 and MinLo calculation. The value given is the probability of observing a distribution with χ^2 greater than or equal to the one observed.

Chapter 5

Coupling measurements and BSM interpretations with 14.8 fb^{-1} at 13 TeV data set

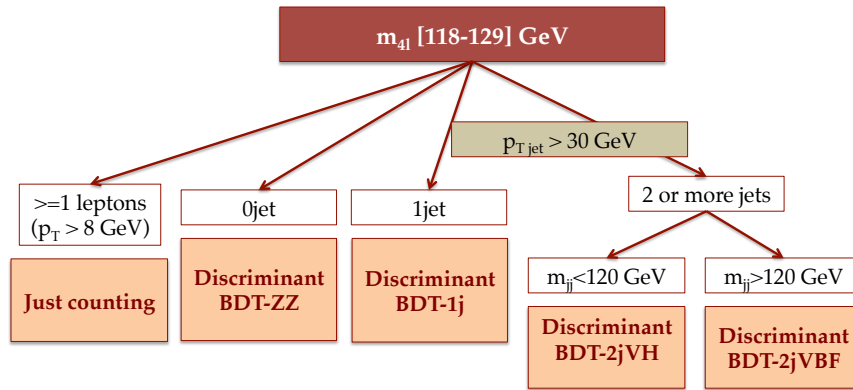


Figure 5.1: Event categorization scheme.

This Chapter presents the measurement of the Higgs production cross sections performed with the 14.8 fb^{-1} data set at 13 TeV collected during Run2. This measurement has been developed to provide a more sensitive measurement to production modes.

The measured exclusive regions of phase space are specific to the different production mechanisms, and motivated by:

- minimizing the dependence on theoretical uncertainties which are directly folded into the measurements;
- maximizing experimental sensitivity;
- isolating possible BSM effects;
- minimizing the number of defined phase spaces without loss of experimental sensitivity.

Considering the limited expected signal yield in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with $L_{int} = 14.8 \text{ fb}^{-1}$ at 13 TeV, the measurement of the cross section per production mode has been performed (Figure 5.2).

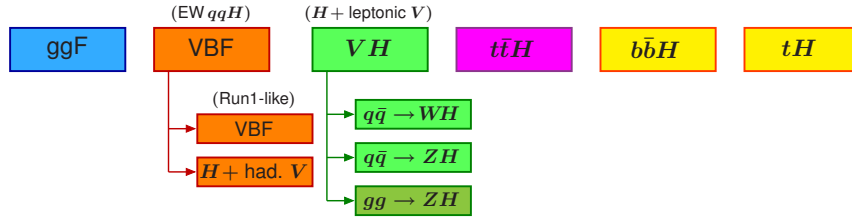


Figure 5.2: Scheme of the production modes.

5.1 The measurement at a glance

5.1.1 Cross section per production mode measurements

In order to measure the cross sections per production mode, categories enriched in each Higgs production mechanism have been defined. This result can be also used for the measurements of coupling modifiers (κ) to SM particles within the k-framework interpretation.

The relation between N_k^{obs} , the observed number of events in each analysis categories (denoted as k), and the cross section in each truth bin σ_i^j (i denotes different production mechanisms and j denotes the index of a phase space or truth bin in the simplified template cross section binning scheme),

can be expressed as follows:

$$\mathcal{N}_k^{\text{obs}} = \mathcal{L}_{\text{int}} \times \mathcal{BR}_{H \rightarrow ZZ^* \rightarrow 4\ell} \times \left(\sum_{i=1}^{\mathcal{N}^{\text{prod}}} \sum_{j=1}^{\mathcal{N}_{\text{bin}}^i} \mathcal{A}_{kj}^i \sigma_i^j \right) \quad (5.1)$$

where $\mathcal{L}_{\text{int}}$ is the integrated luminosity, $\mathcal{N}^{\text{prod}}$ is the number of Higgs production mechanisms, $\mathcal{N}_{\text{bin}}^i$ is the number of truth bins per Higgs production mechanism i , $\mathcal{A}_{kj}^i$ takes into account for detector response (trigger, reconstruction and identification efficiencies) for detecting the final state and the kinematic and geometric acceptance for the truth bin j of Higgs production mechanism i in the analysis category k .

The measurements of couplings for each Higgs production mode are performed using a leading-order tree-level-motivated framework based on the following assumptions:

- the central value of the ATLAS and CMS combined mass measurement of $m_H = 125.09$ GeV is assumed;
- the width of the Higgs boson is narrow, justifying the use of the zero-width approximation;
- only modifications of coupling strengths are considered, while the SM tensor structure is assumed, implying that the observed state is a $\mathcal{CP}$ -even scalar.

The zero-width approximation allows the signal cross section to be decomposed in the following way: $\sigma \cdot BR (i \rightarrow H \rightarrow f) = \sigma_i \cdot \Gamma_f / \Gamma_H$ where σ_i is the production cross section through the initial state i , BR and Γ_f are the branching ratio and partial decay width into the final state f , respectively, and Γ_H the total width of the Higgs boson.

This approach introduces scale factors, “kappas”, applied to the SM Higgs boson coupling which directly probe deviations from the SM predictions. Making a direct example, the ggF production of the ZZ^* final state can be expressed as

$$\sigma(gg \rightarrow H) \cdot BR (H \rightarrow ZZ^*) = \sigma_{\text{SM}}(gg \rightarrow H) \cdot BR_{\text{SM}}(H \rightarrow ZZ^*) \cdot (\kappa_g^2 \cdot \kappa_Z^2) / \kappa_H^2 \quad (5.2)$$

where κ_g , κ_Z , and κ_H are the scale factors for the Higgs couplings to gluon and Z boson, and a scale factor for the total Higgs width, respectively.

Results are extracted from fits to the data using the profile likelihood ratio $\Lambda(\vec{\kappa})$. In the fit, the κ_j are treated either as parameters of interest or as nuisance parameters, depending on the measurement.

5.1.2 Effective Field Theory (EFT) interpretation

This study aims to use both kinematic and rate properties from the different production mechanisms and the $H \rightarrow ZZ^*$ decays to derive information on

the $\mathcal{CP}$ nature of the Higgs boson.

Due to the fact that the VBF and VH production mechanisms are particularly sensitive to possible BSM contributions, an effective field theory (EFT) approach has been adopted in order to describe the interactions between the resonance and the SM vector bosons, following the Higgs boson characterisation model [4] [53].

Among all the possible scenarios, only the hypothesis that the observed resonance is a mixture of spin-0 $\mathcal{CP}$ -even and/or $\mathcal{CP}$ -odd states has been considered, meaning that, in the case of $\mathcal{CP}$ mixing, the Higgs boson would be a mass eigenstate, but not a $\mathcal{CP}$ eigenstate, implying $\mathcal{CP}$ -violation in the Higgs sector.

In all cases, only one resonance with a mass of about 125 GeV is considered; it is also assumed that the total width of the resonance is small with respect to the typical experimental resolution of the ATLAS detector and the interference effects between the signal and SM backgrounds are negligible.

The Higgs Characterization model relies on an EFT approach which, by definition is only valid up to a certain energy scale Λ , set to 1 TeV to account for the experimental results obtained by the LHC and previous collider experiments that show no evidence of new physics at lower energy scales.

The model assumes that the resonance structure corresponds to one new boson, assuming that any other BSM particle exists at an energy scale larger than Λ .

The investigation of possible mixing between the Standard Model $\mathcal{CP}$ -even and BSM $\mathcal{CP}$ -even and $\mathcal{CP}$ -odd contributions is performed, providing a study of the HVV Lagrangian tensor structure.

In the Higgs boson characterization model, the description of the spin-0 particle interaction with pairs of W and Z bosons is given through the following interaction Lagrangian:

$$\begin{aligned} \mathcal{L}_0^V = & \left\{ c_\alpha \kappa_{\text{SM}} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\ & - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\ & \left. - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \right\} X_0. \end{aligned} \quad (5.3)$$

where V^μ represents the vector-boson field ($V = Z, W^\pm$), the $V^{\mu\nu}$ are the reduced field tensors and the dual tensor is defined as $\tilde{V}^{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$. The κ_{SM} , κ_{HVV} and κ_{AVV} denote the coupling constants corresponding to the interaction of Standard Model, BSM $\mathcal{CP}$ -even and BSM $\mathcal{CP}$ -odd spin-0 particles, represented by the X_0 field, with ZZ or WW pairs.

Other higher-order operators [53], namely the derivative operators, are not included in Equation 5.3 and have been neglected in this analysis. To ensure that the Lagrangian terms are Hermitian, these couplings are assumed to be real.

The mixing angle α allows for production of $\mathcal{CP}$ -mixed states and implies $\mathcal{CP}$ -violation for $\alpha \neq 0$ and $\alpha \neq \pi$, provided the corresponding coupling

constants are non-vanishing: the following notation will be used hereafter: $s_\alpha = \sin \alpha$ and $c_\alpha = \cos \alpha$.

The Standard Model coupling strengths, g_{HVV} , are proportional to the square of the vector boson masses: $g_{HVV} \propto m_{Z/W}^2$.

To quantify the presence of BSM contributions in experimentally observed $H \rightarrow ZZ^*$ decay, the observed ratios of couplings κ_{AVV} and κ_{HVV} are measured for the $\mathcal{CP}$ -mixing and anomalous $\mathcal{CP}$ -even contribution scenarios, respectively.

All the models used in these studies are obtained by selecting the corresponding parts of the Lagrangian described in Equation 5.3 while setting all other contributions to zero. The custodial symmetry has been also imposed: in κ_{AVV} and κ_{HVV} $V = W, Z$.

The BSM terms described in Equation 5.3 are also expected to change the relative contributions of the vector-boson fusion (VBF) and vector-boson associated production (VH) processes with respect to the gluon-fusion (ggF) production process, which is predicted to be the main production mode for the SM Higgs boson at the LHC.

For large values of the BSM couplings, the VBF and VH production modes can have a significantly higher cross section due to the fact that the BSM couplings to W/Z bosons enter with the square power in the computation of the cross section. For the VBF and VH Higgs boson events decaying into 4ℓ final state the contribution of κ_{BSM} enters both in production and decay vertexes; while for the ggH, ttH and bbH, κ_{HVV} and κ_{AVV} can only enter in the decay vertex as shown in Figure 5.3.

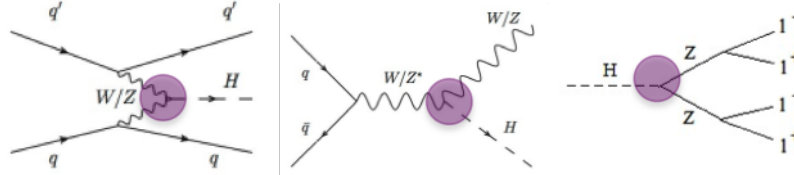


Figure 5.3: Interaction vertices involving the κ_{HVV} and κ_{AVV} BSM coupling considered.

5.2 Higgs EFT samples

The parton-level Monte Carlo generator MadGraph5_aMC@NLO has been used to generate events at leading order for $\sqrt{s} = 13 \text{ TeV}$ proton-proton collisions, allowing Higgs boson-mediated interactions for additional BSM couplings in the production or decay vertexes.

In particular the effective Lagrangian described by the Higgs Characterization model is implemented via the `HC_NLO_X0_UF0` model [54]. This approach allows for the SM and BSM Higgs boson production and decay coupling scale

factors to be set to arbitrary values, as well as the modification of the $\mathcal{CP}$ -mixing term $\cos(\alpha)$.

Scale factors have been applied to the MadGraph5_aMC@NLO generated samples in order to match the YR4 cross sections predictions. This scale factors have been computed for VBF and VH production modes separately and per category. An overall scale factor of 1.11/1.53 is applied to the VBF/VH MadGraph5 generated samples.

Vector boson fusion samples were generated with different values of the $\mathcal{CP}$ -odd coupling scale factor κ_{AVV} and the BSM $\mathcal{CP}$ -even scale factor κ_{HVV} . To facilitate a one-dimensional scan across either κ_{AVV} and κ_{HVV} , four samples have been produced using MadGraph5_aMC@NLO for each case in addition to the SM sample. A *Morphing* technique has then been used in order to extract the signal PDFs from a fixed number of BSM samples over a wide range of BSM coupling values (Section 5.4.2).

5.3 Event categorization

To measure the rates of the different production mechanisms, five categories have been defined depending on the event characteristics and on the number of jets associated to the event, as shown in Figure 5.4:

- VH-leptonic-enriched: requiring an additional lepton in the event ($p_{T,\ell} > 8 \text{ GeV}$),
- 0-jet: $N_{\text{jets}} = 0$,
- 1-jet: $N_{\text{jets}} = 1$ ($p_{T,\text{jet}} > 30 \text{ GeV}$),
- 2-jet VBF-enriched: $N_{\text{jets}} \geq 2$, $m_{jj} > 120 \text{ GeV}$ ($p_{T,\text{jet}} > 30 \text{ GeV}$),
- 2-jet VH-hadronic enriched: $N_{\text{jets}} \geq 2$, $m_{jj} < 120 \text{ GeV}$ ($p_{T,\text{jet}} > 30 \text{ GeV}$).

The VH-leptonic enriched category is defined by the presence of 1 or 2 extra leptons with $p_T > 8 \text{ GeV}$ (e or μ), in addition to the four leptons forming the Higgs boson candidate, coming from the leptonic decay of the vector boson. The presence of at least an additional lepton in the event can also occur in ttH events, where $t \rightarrow Wb$ and the W decays leptonically $W \rightarrow l\nu$. In the future, a ttH -enriched category will be added. Events that fail the VH-leptonic enriched category are then classified according to the jet multiplicity with the kinematic requirement of $p_{T,\text{jet}} > 30 \text{ GeV}$ on the jets. The $p_{T,\text{jet}}$ cut at 30 GeV has been chosen in order to optimize the statistical significance and the sensitivity on the VBF cross section measurement.

The 0-jet category is expected to contain about 53% of the ggF events, is crucial for the ggF production mechanism measurement. The 1-jet category is important for both ggF and VBF production mechanism measurements

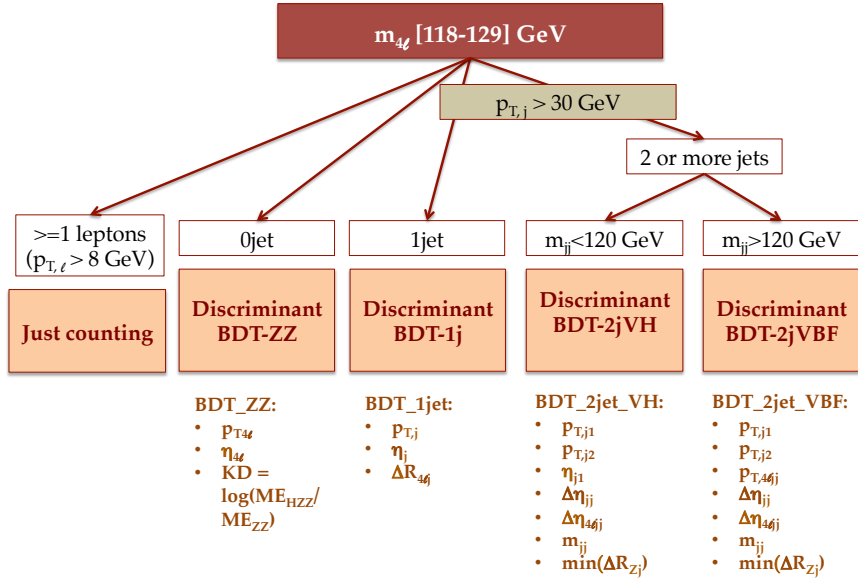


Figure 5.4: Event categorization scheme.

since the $\sim 30\%$ of ggF events and $\sim 30\%$ of VBF events (Figure 5.5) are expected to fall in the 1-jet category; studies have shown that introducing the 1-jet category has improved the precision on the cross section measurement for the VBF production mechanism by $\sim 10\%$. The 2-jet category

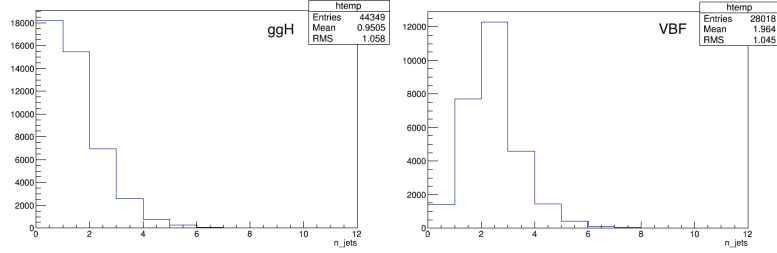


Figure 5.5: Distribution of the number of jets for the ggH and VBF production modes in the $H \rightarrow ZZ^* \rightarrow 4\mu$ decay channel.

is further split into a VH-hadronic enriched category and a VBF enriched one, according to the invariant mass of the di-jet system, where the two jets with the highest p_T are considered if there are more than two jets selected in the event. Events satisfying $m_{jj} < 120 \text{ GeV}$ are assigned to the VH-hadronic-enriched category due to the presence of the vector boson decaying hadronically in association to the Higgs. Events satisfying $m_{jj} > 120 \text{ GeV}$ are therefore assigned to the VBF-enriched category.

The categories defined are quite pure in each production modes they are targeting: Table 5.1 and Figure 5.6 show the SM expected signal composition in each analysis category.

Finally Table 5.2 shows the expected yields in each category, after all analysis criteria and assuming $m_H = 125 \text{ GeV}$, for $L_{\text{int}} = 14.8 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$.

Category	ggF	VBF	WH	ZH	ttH
0-jet	97.6%	1.2%	0.5%	0.6%	0.02%
1-jet	87.6%	8.9%	2.1%	1.4%	0.1%
2-jet VBF-enriched	58.0%	33.9%	2.6%	1.9%	3.6%
2-jet VH-hadronic-enriched	72.8%	6.4%	10.8%	8.0%	1.9%
VH-Leptonic-enriched	7.7%	1.5%	50.2%	7.7%	32.9%
Total	87.1%	8.3%	2.3%	1.5%	0.8%

Table 5.1: Signal composition in each analysis category.

Studies on the categorization In studying possible alternative categorizations, a crucial role has been taken by the possible BSM contributions. MC studies (using MadGraph5) have been carried out on this purpose, show-

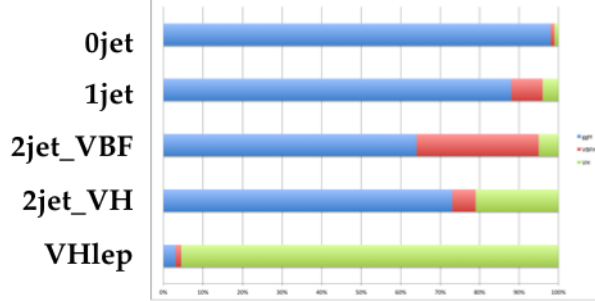


Figure 5.6: Fraction of events per production mode and per category.

Table 5.2: The expected number of events in each category, after all analysis criteria are applied, for each signal production mechanism at $m_H = 125 \text{ GeV}$ for $L_{int} = 14.8 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$. The requirement $118 \text{ GeV} < m_{4\ell} < 129 \text{ GeV}$ is applied.

Category	ggF + $t\bar{t}H$ + $b\bar{b}H$	VBF	WH	ZH
0 jet	11.2 ± 1.1	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006
1 jet	5.7 ± 0.5	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008
2 jet VH enriched	1.05 ± 0.16	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009
2 jet VBF enriched	1.86 ± 0.26	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005
VH-Leptonic	0.055 ± 0.004	0.00217 ± 0.00015	0.067 ± 0.004	0.0105 ± 0.0006
Total	19.8 ± 1.9	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027

ing that the $p_{T,H}$ category splitting is particularly interesting and has been investigated deeply in this measurement. Figure 5.7 shows the difference in the $p_{T,H}$ spectrum for the SM and a BSM sample: it is evident that the BSM contribution directly enters in the high- $p_{T,H}$ regions, but also the low mass shows a bit of sensitivity. Figure 5.8 shows the sensitivity if the di-jet invariant mass (m_{jj}), the leading jet transverse momentum ($p_{T,j1}$) and the transverse momentum of the Higgs ($p_{T,H}$) for the SM and few BSM tests. The $p_{T,j1}$ and $p_{T,H}$ distributions shows a good sensitivity to the BSM samples. Studies have been carried out in this direction in investigating possible further categorizations in $p_{T,H}$ but due to the statistics available it has been decided to only make a counting in each category for the EFT interpretation and the $p_{T,H}$ splitting has been dropped since it also requires to have enough MC statistics to populate the discriminants per category.

5.3.1 Category discriminants

In order to improve the analysis sensitivity, multivariate discriminants have been designed to separate signal from background or among signal for different production modes. In the in the 0-jet category discriminants are built to

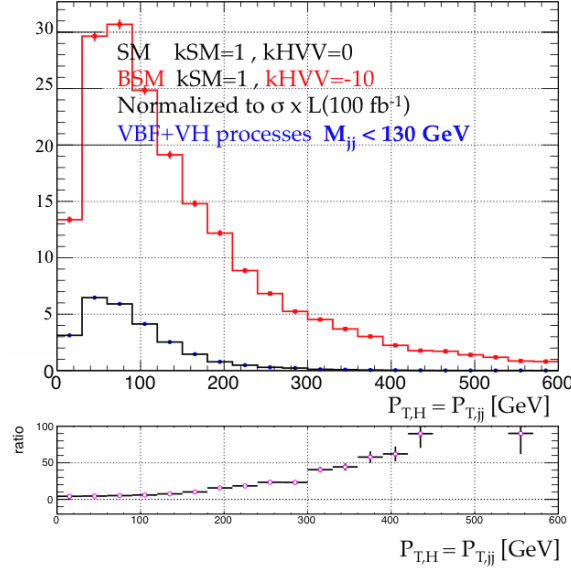


Figure 5.7: BSM sensitivity of the $p_{T,H}$ distribution.

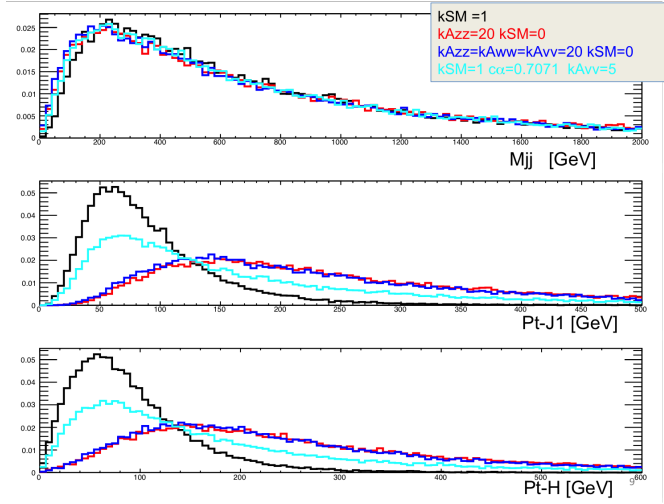


Figure 5.8: BSM sensitivity of the m_{jj} , $p_{T,j1}$ and $p_{T,H}$ distributions for the VBF process.

separate the ggF signal from the ZZ^* background, while in the other categories, discriminants are built to separate the VBF and VH produced Higgs boson signal from the ggF one. Boosted decision tree (BDT¹)-based discriminant have been used relying on its ability to encode information about the final-state lepton and di-jet systems into a single real number, as well as its relative robustness in separating signal with respect to background signatures.

No discriminant has been used in the VH-leptonic enriched category due to the very small yield expected in this category with the statistics available.

5.3.1.1 VH-Leptonic-enriched category

Due to the limited statistics expected in this category, there is no discriminant used for the VH-leptonic enriched category and a simple event counting in this category is used to extract the measurement.

5.3.1.2 0-jet category

For the 0-jet category, mainly populated by ggH events, the discriminant chosen was the BDT trained to separate the Higgs boson ggH signal from the ZZ^* continuum background.

This BDT has been trained on $\sqrt{s} = 13 \text{ TeV}$ Monte Carlo using the following training variables (chosen since they are the most powerful in discriminating between those):

$$p_T^{4\ell}, \eta_{4\ell}, \mathcal{KD}_{ZZ}.$$

The kinematic discriminant is computed as $\mathcal{KD}_{ZZ} = \log(|\mathcal{M}_{HZZ^*}|^2/|\mathcal{M}_{ZZ^*}|^2)$, where the numerator and denominator represent matrix element calculations for leading order gluon fusion produced $H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$ production, and $qq \rightarrow ZZ$ continuum background, respectively. Figure 5.9 presents the training and testing output of the BDT, while in Figure 5.10, the ROC curve is presented².

Figure 5.11 shows the distributions of BDT_{ZZ} for each Higgs boson production mode considered, as well as for the ZZ continuum background.

5.3.1.3 1-jet category

Approximately $\sim 30\%$ of VBF and ggF events will end up in having only one reconstructed jet, therefore an important consideration in building the discriminant for this category is aiming for the separation between this two

¹The BDT is a bunch of if-statements which in the end returns -1 or +1 respectively for pure background like or signal like tests.

²In statistics, a Receiver Operating Characteristic curve (ROC curve), is a graphical plot that illustrates the performance of a binary classifier system as its discrimination threshold is varied.

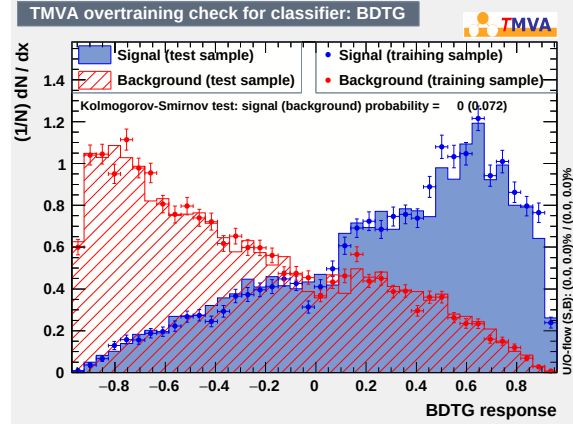


Figure 5.9: Distributions of BDT_{ZZ} for the training and testing samples.

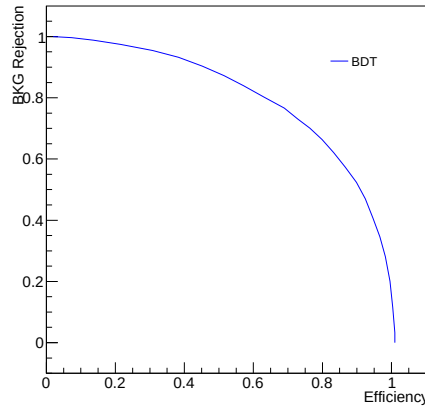


Figure 5.10: ROC curve for the BDT_{ZZ} distribution.

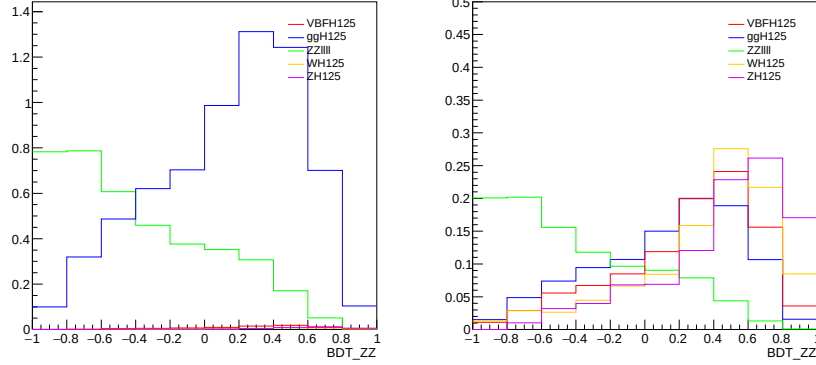


Figure 5.11: Distributions of BDT_{ZZ} for Higgs boson signal and ZZ continuum background normalized to the events expected for 10 fb^{-1} at 13 TeV (left) and normalized to unity (right).

production mechanisms.

To this end, the discriminating power of the BDT trained on the following variables has been chosen:

$$p_{T(jet)}, \eta_{(jet)}, \Delta R(j, ZZ)$$

The quantity $\Delta R(j, ZZ)$ represents the $\sqrt{\Delta\eta^2 + \Delta\phi^2}$ between the reconstructed jet and ZZ system, which is analogous to the quantity $\min(\Delta R_{jZ})$ used in the BDT for the 2-jet, VBF-enriched category.

Figure 5.12 shows the distributions of these quantities for the ggF (in red, denoted as background in this category) and VBF (in blue) processes. Figure 5.13

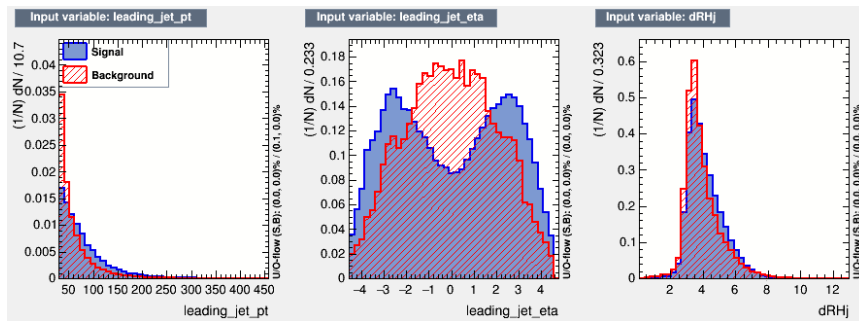


Figure 5.12: Discriminating variables considered for training the BDT for the 1-jet, VBF-enriched region, from left to right, $p_{T(jet)}, \eta_{(jet)}, \Delta R(j, ZZ)$.

shows the distributions of BDT_{1j} for each Higgs boson production mode considered, as well as ZZ continuum background.

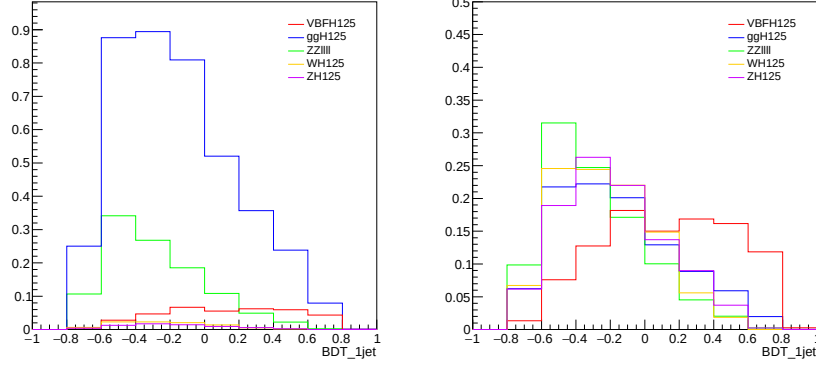


Figure 5.13: Distributions of BDT_{1j} for Higgs boson signal and ZZ continuum background normalized to the events expected for 10 fb^{-1} at 13 TeV (left) and normalized to unity (right).

Alternative discriminant

Several discriminants have been tested for this purpose: differences among them are at few % level impact on the sensitivity to the VBF cross section (negligible impact on the ggF cross section, whose measurement his lead by the 0jet category). The BDT_{1jet} trained using the

$$p_{T(jet)}, \eta_{(jet)}, ME_{VBF}^{ud}$$

is described (Feynman diagrams involved in the ME_{VBF}^{ud} are reported in Figure 5.14). In order to define the ME_{VBF}^{ud} , truth studies have been per-

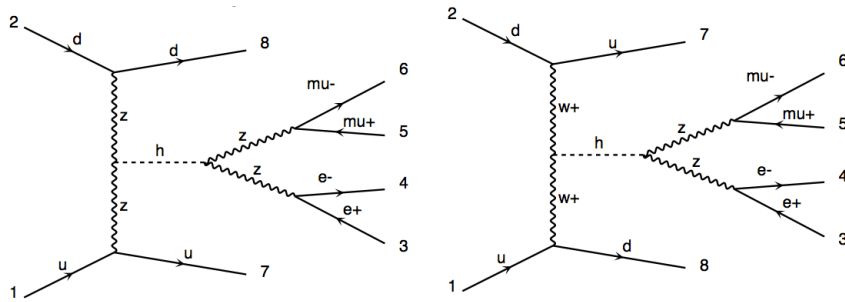


Figure 5.14: Feynman diagrams involved in computing the ME_{VBF}^{ud} .

formed to obtain information on the not reconstructed jet. As shown in Figures 5.15 and 5.16 the not reconstructed jet in VBF events falling in the 1jet category has mostly:

- $\eta = \pm 3.3$, opposite to the leading jet;

- $p_{T,jet} = 23 \text{ GeV}$;
- $\phi = \text{randomly distributed}$.

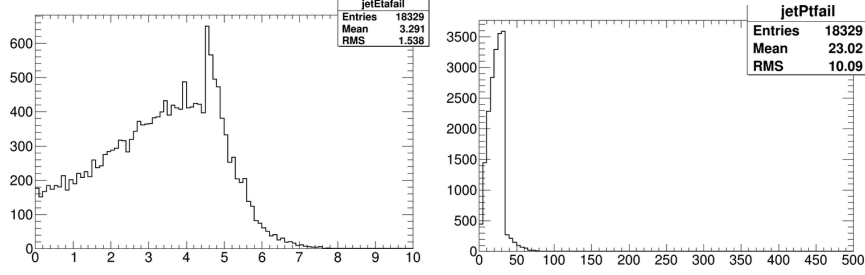


Figure 5.15: Truth studies in the 1jet category for the VBF events. The η and p_T distributions of the not reconstructed jet are reported.

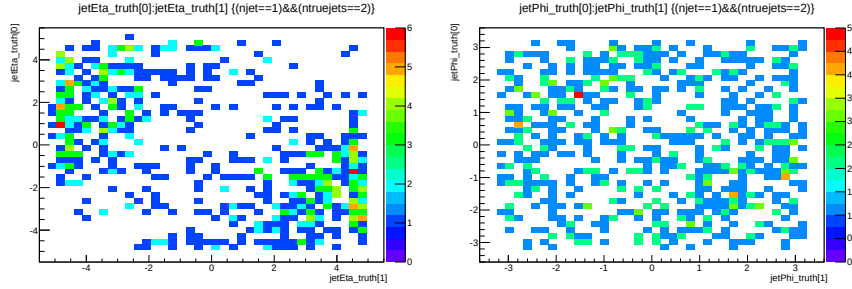


Figure 5.16: Truth studies in the 1jet category for the VBF events. The η and ϕ of subleading jet versus the leading jet 2D distributions are reported.

The distributions of the variables used in the BDT_{1jet} training ($p_{T(jet)}$, $\eta_{(jet)}$, ME_{VBF}^{ud}) are reported in Figure 5.17 for the different production modes, while Figure 5.18 shows the BDT_{1jet} distribution for different production modes and the ROC curve where the signal is the VBF production mode.

5.3.1.4 2-jet VBF-enriched category

Concerning the 2-jet VBF enriched category, the primary requirement in building the discriminant is the separation of VBF production from di-jet gluon fusion events, which could otherwise contaminate the yield in this category by up to 40%.

The BDT used in the 2jet high di-jet-mass category is based on the following variables: the jet transverse momenta ($p_{T(jet1)}$ and $p_{T(jet2)}$), the di-jet invariant mass (m_{jj}), the pseudorapidity separation between the two leading

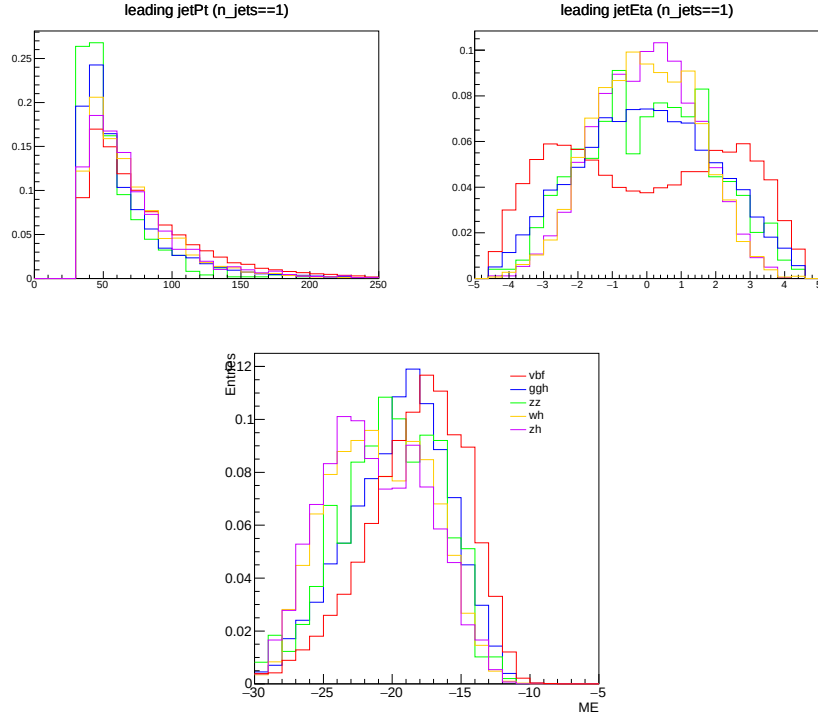


Figure 5.17: Distributions of $p_{T(jet)}$, $\eta_{(jet)}$, ME^{ud}_{VBF} for different production modes.

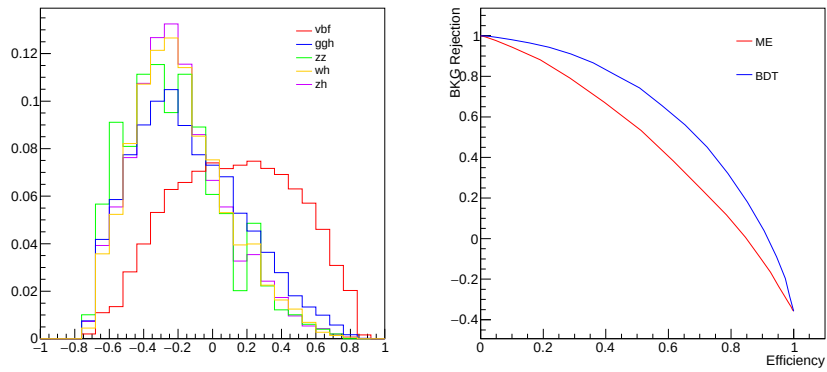


Figure 5.18: Distributions of BDT_{1jet} for different production modes and ROC curve for the VBF signal in the 1jet category.

jets ($\Delta\eta_{jj}$), the transverse momentum of the di-jet plus four-lepton system ($p_T^{4\ell jj}$), the minimum angular separation between the leading di-lepton pair and the two leading jets ($\min(\Delta R_{jZ})$) and the difference in pseudorapidity between the four-lepton system and the average pseudorapidity of the two leading jets ($\Delta\eta_{4\ell jj}$) which tends towards values of zero for VBF-like configurations of a central Higgs boson with forward, back-to-back jets. The distributions of the selected training variables can be found in Figure 5.19. In order to avoid large theoretical uncertainties stemming from

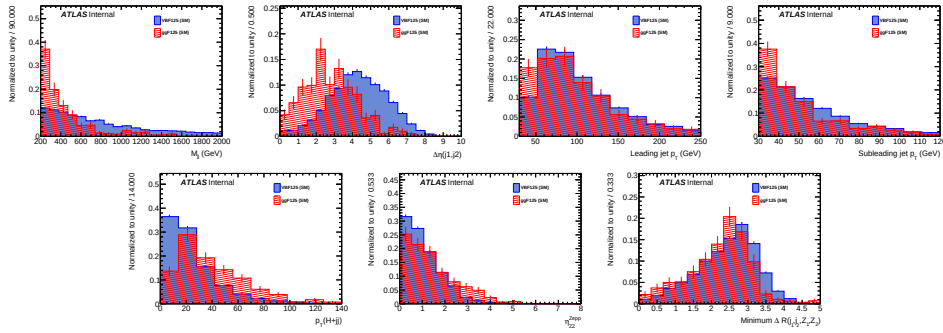


Figure 5.19: Discriminating variables considered for training the BDT for the two-jet, VBF-enriched region.

the use of tight cuts on the Higgs-dijet system transverse momentum $p_T^{4\ell jj}$, the value of $p_T^{4\ell jj}$ was modified to an “infrared-safe” form during training and application of the BDT, defined as follows,

$$p_T^{4\ell jj} = \begin{cases} p_T^{4\ell jj} & \text{if } p_T^{4\ell jj} > 50\text{GeV} \\ 50\text{GeV} & \text{if } p_T^{4\ell jj} < 50\text{GeV} \end{cases} \quad (5.4)$$

This approach limits the size of the associated NLO QCD scale variation uncertainty to $\mathcal{O}(20)\%$, as calculated using the Stewart-Tackmann method [52]. Figure 5.21 shows the distributions of the BDT_{2j}^{VBF} for each Higgs boson production mode considered, as well as ZZ^* continuum background.

Alternative discriminant

Several discriminants have been tested for this purpose that differ within few % among each other on the impact to the sensitivity to the VBF cross section (negligible impact on the ggF cross section, whose measurement is lead by the 0jet category). Figure 5.22 shows the normalized shapes of the KD distribution ($KD = \ln(ME_{VBF}^{uux})/\ln(ME_{ggF}^{uux})$) in the 2jet VBF-enriched category for different production modes in two regions of $p_{T,H}$ ($> / < 125$ GeV).

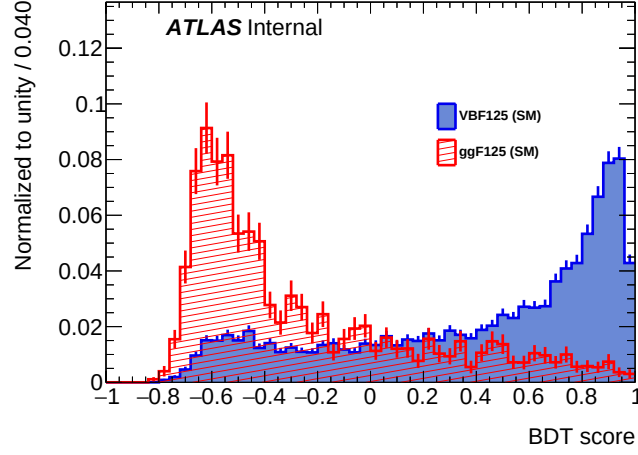


Figure 5.20: BDT-based dijet discriminant used in the 2-jet, VBF-enriched category.

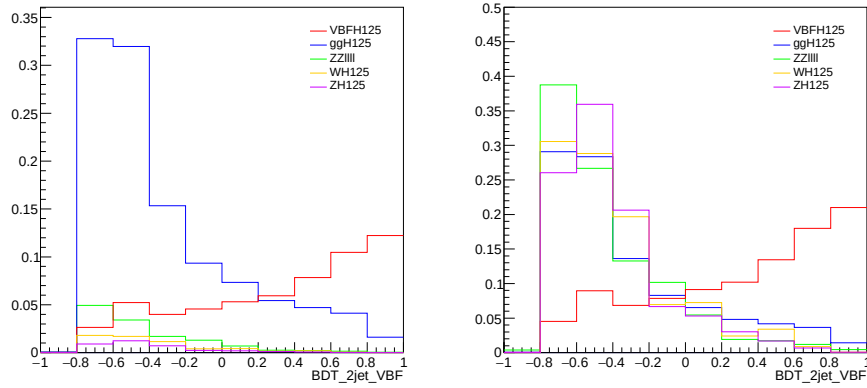


Figure 5.21: Distributions of BDT_{2j}^{VBF} for Higgs boson signal and ZZ continuum background normalized to the events expected for 10 fb^{-1} at 13 TeV (left) and normalized to unity (right).

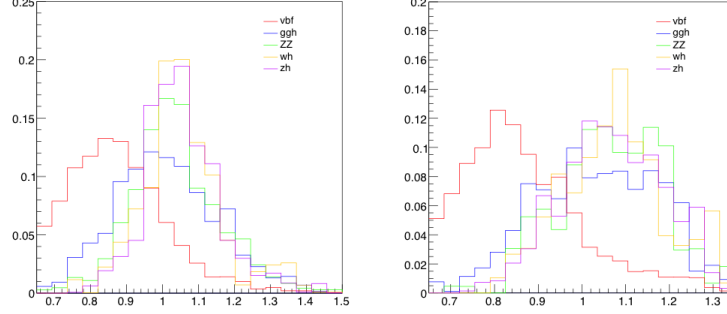


Figure 5.22: KD distribution ($KD = \ln(ME_{VBF}^{uux})/\ln(ME_{ggF}^{uux})$) in the 2jet VBF-enriched category for different production modes for $p_{T,H}$.

5.3.1.5 2-jet VH-hadronic-enriched category

Similar to the 2-jet VBF-enriched category, a BDT was trained to separate VH and VBF+ggF-mediated Higgs boson production processes. For the 2jet low di-jet mass the same variables have been used in training the BDT with the exception of the $p_T^{4\ell jj}$ (this variable bringing little improvement in the low-mass category) but adding the pseudorapidity of the leading jet (η_{jet1}). The distributions of the training variables is shown in Figure 5.23: among them, the invariant mass of the di-jet system clearly shows a peaked distribution around 90 GeV for the VH sample, due to the ZH component, with the Z decaying hadronically. By including the BDT as a discriminant in the

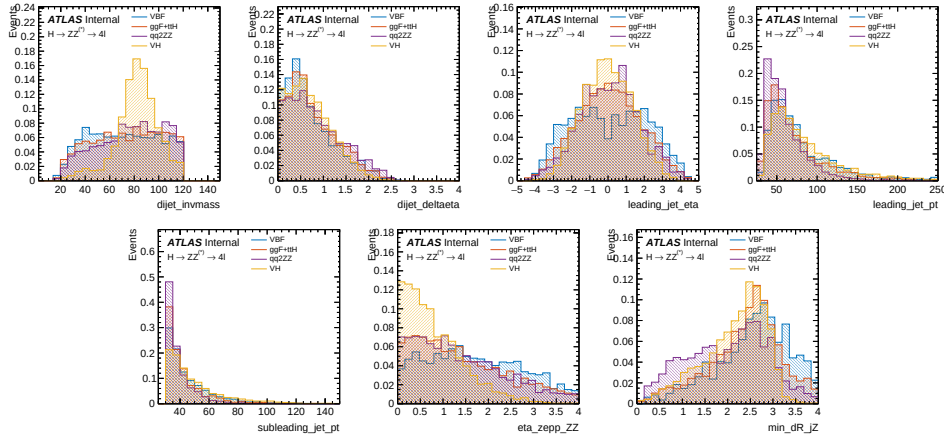


Figure 5.23: Discriminating variables considered for training the BDT for the two-jet, VH-enriched region.

VH category, an improvement of 10% in the signal strength uncertainty on VH was observed.

Figure 5.24 shows the distributions of BDT_{2j}^{VH} for each Higgs boson production modes as well as the ZZ^* continuum background.

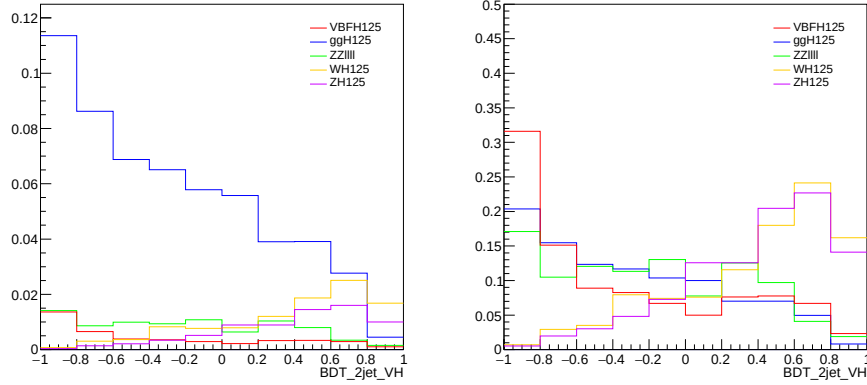


Figure 5.24: Distributions of BDT_{2j}^{VH} for Higgs boson signal and ZZ continuum background, normalized to the events expected for 10 fb^{-1} at 13 TeV (left) and normalized to unity (right).

Alternative discriminant

In this case also the invariant mass of the di-jet system (m_{jj}) can be used as a discriminant for this category since ZH events in which the Z boson decays hadronically show a peak corresponding to the Z boson mass. Figure 5.25 shows the normalized shapes of the m_{jj} distribution in the 2jet VH-enriched category for different production modes. This discriminant has been found not to be optimal for this category: the BDT_{2j}^{VH} shows a better sensitivity on the VH production mode of the order of few %.

5.3.2 Signal acceptance in categories

Signal acceptance factors include the detector correction factor, computed as the ratio of the number of signal MC events satisfying the event selection criteria in each analysis category over the total number of events generated in the full phase space. MC samples generated with Higgs mass at 125 and 126 GeV have been used on this purpose and a linear interpolation between these two mass points have been performed to extract the results for Higgs signals with mass of 125.09 GeV.

The Signal acceptance times correction factor ($CF = 1/\epsilon$) for each signal process in each analysis category is reported in Table 5.3.

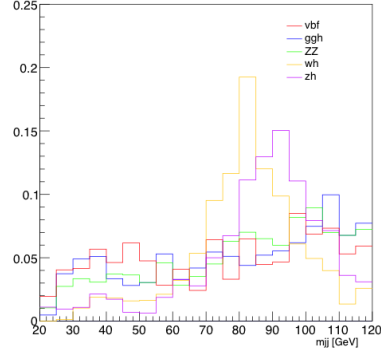


Figure 5.25: Normalized distribution of the invariant mass of the di-jet system in the 2jet VH-enriched category for different production modes.

Category	ggF	VBF	WH	ZH	ttH
0-jet	0.125	0.0174	0.0189	0.0373	0.000125
1-jet	0.0636	0.0856	0.0551	0.0570	0.00096
2-jet VBF-enriched	0.0198	0.0134	0.0296	0.0325	0.107
2-jet VH-hadronic-enriched	0.0115	0.0123	0.0576	0.0631	0.0276
VH-Leptonic-enriched	0.000127	0.000313	0.0270	0.00661	0.0479

Table 5.3: Signal acceptance times correction factor for each signal process in each analysis category.

5.3.3 Background estimates in categories

5.3.3.1 ZZ^* background estimates in categories

The expected yields and shapes in each category are based on Powheg MC samples while Sherpa has been used for systematic studies.

A side band region can be defined by applying all the analysis cuts, but looking in a $m_{4\ell}$ region orthogonal to the signal region, i.e. by requiring $m_{4\ell} < 110 \text{ GeV}$ or $m_{4\ell} > 140 \text{ GeV}$.

Those side bands are dominated by ZZ^* background and serve as a validation for its modelling. Table 5.4 shows the number of events observed in data compared to the expected number of events in the side band region for each category.

Figure 5.26 shows the distribution of the BDT discriminants of each category in this control region; both normalization and shapes for the ZZ^* background are taken from MC expectations since reasonable agreement is shown in the side bands.

Table 5.4: Number of events observed in data for the side band region compared to MC estimates.

Final State	Data	Total MC	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	$t\bar{t}+V, VVV$
0 jet	312	299.68	0.17	293.20	5.71	0.60
1 jet	102	129.56	0.11	122.76	5.70	0.99
2 jet VH enriched	23	24.75	0.03	18.15	5.70	0.87
2 jet VBF enriched	53	35.05	0.06	26.36	5.69	2.94
VH-Leptonic enriched	1	3.10	0.09	0.59	1.95	0.47
All	491	492.14	0.46	461.06	24.75	5.87

5.3.3.2 Reducible background estimates in categories

The measurements for the reducible background $Z+\mu\mu$ and $Z+ee$ channels have been already discussed in Chapter 3.

The fraction of events falling in a given category with respect to the inclusive yield of MC-simulated Z -jets and $t\bar{t}$ samples is used to scale the data-driven estimate and checked in control regions.

The shapes of the reducible backgrounds for a given observable are also taken from MC simulation, relaxing the isolation selections to enhance the statistics. The results are summarized in Table 5.5. In cases where there are no statistics in the MC for a category, a limit is extracted and used as the uncertainty. For the shapes used in the fits, the reducible background shapes are simply obtained by summing the $Z+\text{jet}$ and $t\bar{t}$ MC distributions by relaxing the isolation selections to enhance the statistics. Figure 5.27 presents the resultant shapes for the BDT discriminants in each analysis category.

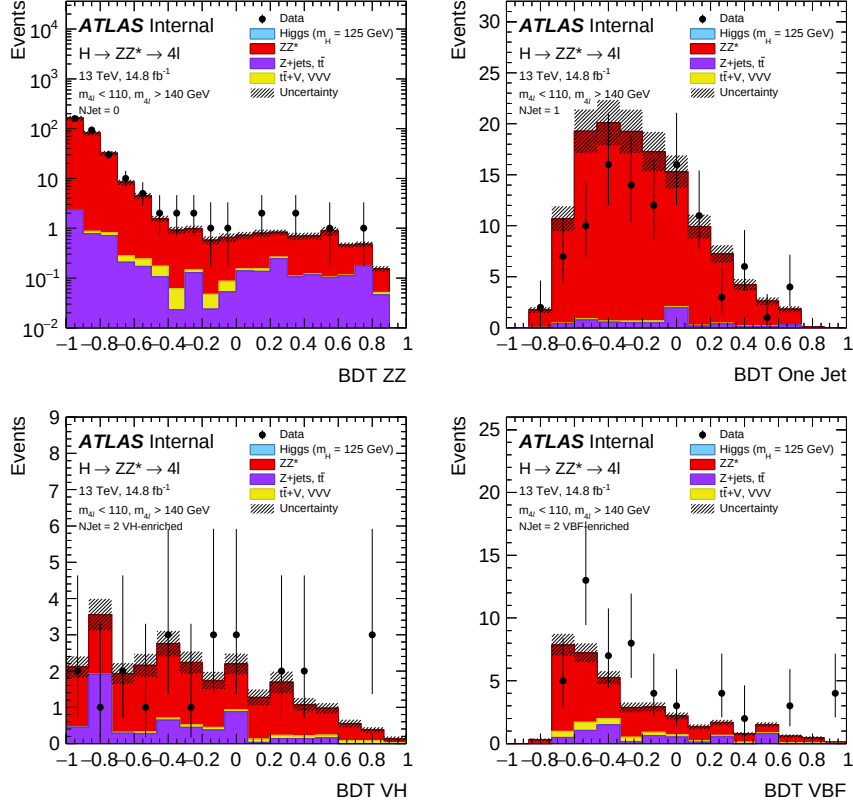


Figure 5.26: Various distribution of the selected candidates in the $m_{4\ell} < 110 \text{ GeV}$ or $m_{4\ell} > 140 \text{ GeV}$ for data compared to the background expectation in the different categories.

Table 5.5: The estimation of reducible background in analysis categories with relaxing the isolation selections for 14.8 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

Categories	Central value	Stats. and syst. unc.
0-jet	0.836	0.121
1-jet	0.423	0.072
2-jet VBF-enriched	0.201	0.109
2-jet VH-Hadronic-enriched	0.073	0.011
VH-Leptonic-enriched	0.010	0.010

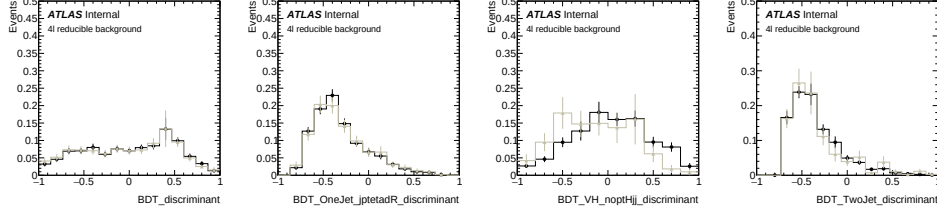


Figure 5.27: The shape of the reducible backgrounds from relaxing the isolation selections to enhance the statistics. The discriminant distributions for the 0-jet (top left), 1-jet (top right), 2-jet VBF enriched (bottom left), and 2-jet VH-hadronic enriched (bottom right) category are shown.

5.4 Signal and background modelling for the SM coupling and EFT measurements

5.4.1 PDFs for the SM coupling measurements

For each analysis category considered, one dimensional binned PDFs of the BDT discriminants described in the previous section have been used. Figure 5.28 shows the PDFs for signal and backgrounds of the discriminants in each category.

In the 0-jet, 1-jet, and ≥ 2 -jet VBF-enriched categories, 15 bins are used, while 10 bins are used in the 2-jet VH-Hadronic category. Event counting is used in VH-Leptonic category, meaning that there is effectively one bin in the binned PDF.

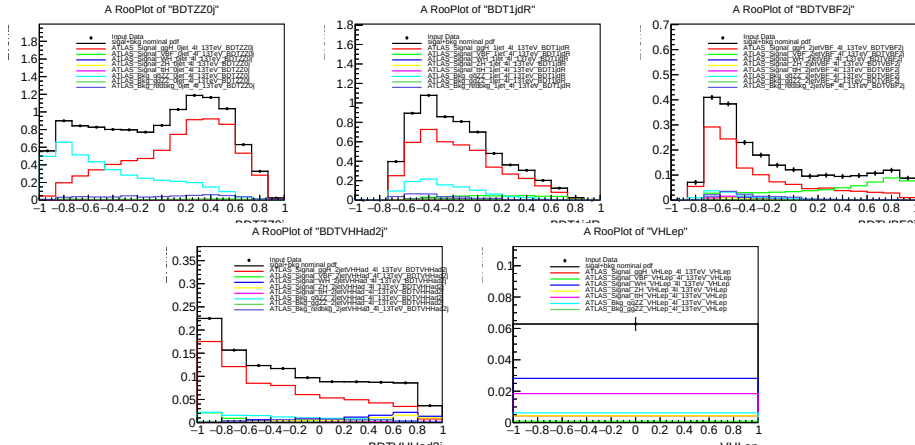


Figure 5.28: PDF shapes in each category, from left to right: 0-jet, 1-jet, 2-jet VBF-enriched, 2-jet VH-Hadronic-enriched, VH-Leptonic, and the SM Asimov dataset.

5.4.2 PDFs for the BSM coupling measurements

Concerning the EFT studies, samples have been produced using MadGraph5_aMC@NLO and a *Morphing* technique has been used in order to extract the signal PDFs from a fixed number of BSM samples over a wide range of BSM coupling values.

To understand the basic concepts of the *Morphing*, an example can be given considering the ZZ^* decay of a Higgs boson in the EFT framework with only two parameters: κ_{SM} , which is a Standard Model coupling parameter for HZZ vertex and κ_{AZZ} , which is the coupling parameter of the $\mathcal{CP}$ -odd Higgs boson state to two Z -bosons.

To study the distributions for some particular values of κ_{SM} and κ_{AZZ} (i.e. to obtain the sample $S(\kappa_{SM}, \kappa_{AZZ})$) the following procedure has been applied:

$$\begin{aligned} S(\kappa_{SM}, \kappa_{AZZ}) &\propto |\kappa_{SM}\mathcal{M}_{SM} + \kappa_{AZZ}\mathcal{M}_{AZZ}|^2 = \kappa_{SM}^2|\mathcal{M}_{SM}|^2 + \\ &\kappa_{SM}\kappa_{AZZ}(\mathcal{M}_{SM}M_{AZZ}^\dagger + \mathcal{M}_{AZZ}M_{SM}^\dagger) + \kappa_{AZZ}^2|\mathcal{M}_{AZZ}|^2 = (\kappa_{SM}^2 - \\ &\kappa_{SM}\kappa_{AZZ})|\mathcal{M}_{SM}|^2 + \kappa_{SM}\kappa_{AZZ}|\mathcal{M}_{SM} + \mathcal{M}_{AZZ}|^2 + (\kappa_{AZZ}^2 - \kappa_{SM}\kappa_{AZZ})|\mathcal{M}_{SM}|^2, \end{aligned} \quad (5.5)$$

where $\mathcal{M}_{xx}$ is a matrix element of corresponding process. Finally, we obtain,

$$\begin{aligned} S(\kappa_{SM}, \kappa_{AZZ}) &= (\kappa_{SM}^2 - \kappa_{SM}\kappa_{AZZ})S_{SM} + \\ &\kappa_{SM}\kappa_{AZZ}S_{\text{Mix}} + (\kappa_{AZZ}^2 - \kappa_{SM}\kappa_{AZZ})S_{AZZ}, \end{aligned} \quad (5.6)$$

where S_{SM} is a pure Standard Model sample ($\kappa_{SM} = 1$), S_{AZZ} is a pure BSM sample ($\kappa_{AZZ} = 1$), and the S_{Mix} sample corresponds to the coupling values $\kappa_{SM} = \kappa_{AZZ} = 1$.

In this case, it is therefore possible to construct a sample with arbitrary coupling values by combining just three *base samples* with the corresponding weights.

The number of *base samples* needed to perform the morphing depends on the model under investigation. For example, for the VBF process, assuming $\kappa_{ZZ} = \kappa_{WW}$ and only one BSM coupling entering in the HZZ vertices ($n_s = 2$), only five samples are required, but if in the same vertices three more BSM couplings are considered ($n_s = 5$), the required number of base samples will increase to 70.

Only studies involving one BSM coupling contribution at a time will be discussed, setting all the other BSM components in Equation 5.3 to zero. The number of *base samples* needed for analysis are reported in Table 5.6.

5.4.3 Total width studies on EFT samples

As described in Section 5.2, the Monte Carlo generator MadGraph5_aMC@NLO is employed to generate vector boson fusion $H + \text{jets}$ samples. In the Monte

N of base sample	ggF	VBF
κ_{HVV}	3	5
κ_{AVV}	3	5

Table 5.6: List of number of morphing base samples N needed for the tensor coupling analysis presented.

Carlo generation, the total width of the Higgs Boson was kept fixed to the Standard Model calculations (Γ_{SM}) such that the Branching Ratios (BRs) in all the samples were calculated as,

$$BR_j = \frac{\Gamma_j}{\Gamma_{SM}}. \quad (5.7)$$

In the case of the introduction of a BSM contribution, the usage of a fixed value (Γ_{SM}) for the total width of the Higgs Boson would not be correct. In particular, it is necessary to calculate the change in the total width according to the introduction of the BSM contributions.

Γ_{BSM} is therefore defined as the total width of the Higgs Boson when introducing BSM contributions.

There are two possible scenarios:

- $\Gamma_{SM} > \Gamma_{BSM}$: the calculated BRs are an underestimation of the correct BR and the total sum of the BRs will be smaller than 1: this means an underestimation of the number of events expected for the BSM contribution.
- $\Gamma_{SM} < \Gamma_{BSM}$: the calculated BRs are an overestimation of the correct BR and the total sum of the BRs will be larger than 1: this means an overestimation of the number of events expected for the BSM contribution.

In the SM case, the contribution of the different BRs to the total width is known ($BR(WW) = 0.214$, $BR(ZZ) = 0.026$ and $BR(\text{others}) = 0.760$), hence $\frac{\Gamma_{BSM}}{\Gamma_{SM}}$ can be written in the form:

$$\frac{\Gamma_{BSM}}{\Gamma_{SM}} = 0.760 + 0.214 \times f_{KxWW}^{BR} + 0.026 \times f_{KxZZ}^{BR}, \quad (5.8)$$

where f_{KxWW}^{BR} and f_{KxZZ}^{BR} are the functions describing the change in BR for the WW and ZZ decays, respectively; these functions are different for κ_{AVV} and κ_{HVV} , and are labelled as $KxWW$ and $KxZZ$. The factors described in 5.8 can be easily calculated once the functions for the BRs are defined. f_{KxYY}^{BR} can be described as a second order polynomial of the form:

$$f_{KxYY}^{BR} = a \times K_{SM}^2 + b \times K_{xYY}^2 + c \times K_{SM} \times K_{xYY}. \quad (5.9)$$

where the factors a , b , and c can be calculated looking directly at the cross section obtained via generator-level Monte Carlo for three different ggF samples generated using the LO MadGraph5_aMC@NLO.

The inverse of the function is presented because it directly represents the necessary factor to apply to the generated MadGraph5_aMC@NLO sample to fix the total width problem. As it is shown in Figure 5.29, in the whole range of κ_{AVV} values, the value of $\frac{\Gamma_{SM}}{\Gamma_{BSM}}$ is smaller than one: this means that $\Gamma_{BSM} > \Gamma_{SM}$, hence the number of events directly estimated via Monte Carlo is an overestimation of the correct expectation. However, the difference is small, so the impact on the change in the total width is also expected to be small (on the order of a few percent). In the case of κ_{HVV}

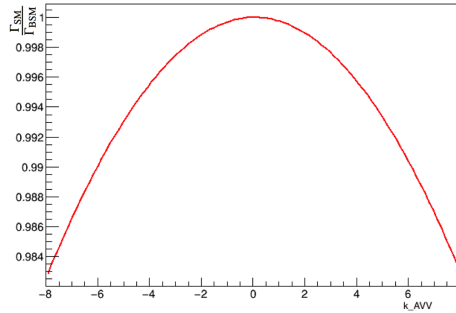


Figure 5.29: Γ_{SM}/Γ_{BSM} over a range of κ_{AVV} . Since $\Gamma_{BSM} > \Gamma_{SM}$, the number of events directly estimated via Monte Carlo is an overestimation of the correct expectations.

(Figure 5.30) it is shown that the condition $\Gamma_{BSM} < \Gamma_{SM}$ is valid for a small range of values: these values correspond to an interference among the SM and BSM contributions which causes a difference among the negative and positive sides of the κ_{HVV} scan.

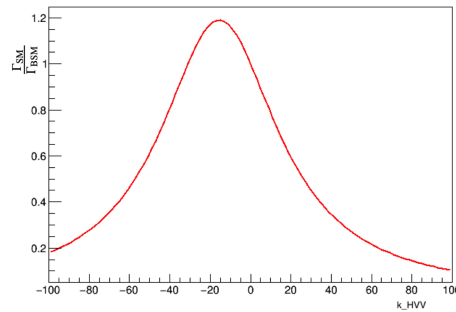


Figure 5.30: Γ_{SM}/Γ_{BSM} in case of κ_{HVV} . A wider range of values of κ_{HVV} is presented to give a full picture of the values that Equation 5.8 assumes for κ_{HVV} .

5.4.4 The likelihood function to extract the signal per production mode

The analysis built to extract the cross section per production mode relies on discriminant observables chosen in different categories to be sensitive to the different SM Higgs boson production mechanisms while preserving the discrimination against the various backgrounds as described in Section 5.4.4. A likelihood function $\mathcal{L}(\vec{\sigma}, \vec{\theta})$ that depends on the cross section of the different Higgs boson production mechanisms, is then constructed as a product of conditional probabilities over binned distributions of the discriminant observables in each category.

The cross sections are treated as an independent parameters for each production mechanism and correlated among the different categories.

The test statistic used to extract the results is based on the q-test, i.e. the ratio of profile likelihoods ($q = 2NLL_{inj} - 2NLL$) where in the $2NLL_{inj}$ the cross section values are fixed to the SM predictions, the $2NLL$ the cross sections are free parameters in the fit.

The value of the test statistic is used to compare the probabilities of hypothesis and construct a likelihood scan over the parameter of interest (i.e. the cross sections per production mode).

Large values of q are interpreted as the data being in disagreement with the tested hypothesis (SM).

5.4.4.1 Signal extraction for the EFT analyses

The tensor coupling analysis relies on the rate information in different categories since no shape information is taken from the discriminant observables but only their normalization.

A likelihood function that depends on the tensor coupling assumption of the signal, $\mathcal{L}(\vec{K}_x, \vec{\theta})$, is constructed as a product of conditional probabilities over rate information in each category:

$$\mathcal{L}(\text{data} \mid \vec{K}_x, \vec{\theta}) = \prod_j^{N_{\text{categories}}} P(N_j \mid \cdot S_j^{(\vec{K}_x)}(\vec{\theta}) + B_j(\vec{\theta})) \times \mathcal{A}_j(\vec{\theta}), \quad (5.10)$$

where $\vec{K}_x$ represents the choice of the couplings for a specific hypothesis. The signal rates are not profiled but taken directly from the theory prediction. The symbol $\vec{\theta} = \{\theta_1, \theta_2, \dots, \theta_N\}$ represents all nuisance parameters.

The likelihood function is a product of Poisson distributions P corresponding to the observation of N_j events in each category given the expectations for the signal, $S_j^{(\vec{K}_x)}(\vec{\theta})$, and for the background, $B_j(\vec{\theta})$. Some of the nuisance parameters are constrained by auxiliary measurements. Corresponding constraints are represented by the functions $\mathcal{A}_j(\vec{\theta})$.

In the likelihood, the signal expectations $S_j^{(\vec{K}_x)}(\vec{\theta})$ are parametrized in terms

of the SM and BSM couplings using the *Morphing* technique described in Section 5.4.2.

The test statistic q used to investigate the EFT couplings is based on a ratio of profiled likelihoods; the value of the test statistic is used to compare the different probabilities of the hypotheses and construct a likelihood scan over the parameter of interest. In this analysis, the SM couplings are fixed to their theory values ($k_{SM} = 1$) and only one BSM coupling is considered at a time.

For this reason, the only parameter of interest is the BSM coupling.

5.5 Uncertainties

The systematic uncertainties in this analysis can be divided into experimental and theoretical systematics. The former includes uncertainties on the modeling of the physics objects (leptons and jets reconstruction, identification efficiencies, energy resolution and scale) and on the total integrated luminosity. The latter includes uncertainties on the modeling of the signal and the background processes.

Since events are categorized according to jet multiplicity, systematic uncertainties originating from the jet energy scale and resolution are accounted for, together with uncertainties on the procedure used to derive the data-driven background estimates.

The systematic uncertainty associated with a given NP is estimated bin-by-bin comparing the nominal event yield with what obtained varying the NP by one standard deviation (up/down).

The largest systematic contribution for ggF events originates from jet energy scale variations, observed in the ≥ 2 -jet VBF/VH-enriched categories: the corresponding contribution for the most populated 0 and 1-jet categories is about a factor of 2 lower. The tree-level VBF signature is accompanied by two jets but it can also enter in the 0 and 1-jet categories if one or both jets are not reconstructed ($p_{T,jet} > 30 \text{ GeV}$); as a result, the largest systematic contribution for the VBF process from jet energy scale variations is seen for low jet multiplicity categories. The ZZ^* background has similar kinematic distributions as the ggF process, therefore its largest corresponding systematic uncertainties are observed for the ≥ 2 -jet VBF/VH-enriched categories.

5.5.0.2 Experimental systematics

Lepton identification and reconstruction efficiencies, energy/momentum scale and resolution have been derived from data using samples of $J/\psi \rightarrow \ell\ell$ and $Z \rightarrow \ell\ell$ decays. Typical uncertainties on the lepton identification efficiencies, evaluated with the tag-and-probe method, are in the range between 0.5 – 1.0% for muons and 1.0 – 1.3% for electrons. The uncertainty on the

electron and muon energy scale and resolution are small and have a negligible impact on the analyses.

Concerning jets, the transverse jet energy scale, derived as a correction that relates the reconstructed jet energy to the truth one, and the resolution uncertainties are in the range 3–7% and 2–4%, respectively. The measurement of the cross section of the VBF production mode of course is the most affected by this systematics, whose impact is of the order of 15%.

The uncertainty on the integrated luminosity, derived following the method based on beam-separation measurements (also known as Van der Meer scans), is 2.1% for the 2015 data set and 3.7% for the 2016 data set.

The reducible backgrounds are estimated using data-driven techniques, as discussed in Chapter 3. Their estimates are extracted with a precision of 14% for both the $\ell\ell + ee$ and $\ell\ell + \mu\mu$ final states. The larger uncertainty in the $\ell\ell + \mu\mu$ final states comes from the limited statistics in computing the simulation-based extrapolation factor for the Z+light-flavour jet component. In addition to the error on the yield for the different experimental categories, uncertainties are also derived for the distributions of the discriminants used in the different analyses.

The precision of the Higgs boson mass measurement as obtained from the ATLAS-CMS combination, $m_H = 125.09 \pm 0.24\text{ GeV}$ [5], has been taken into account in the systematic uncertainties. It affects the signal extraction via the mass distribution in the total cross section measurement or the mass window acceptance for the categorized signal extraction.

5.5.0.3 Theoretical systematic uncertainties

Theoretical uncertainties in fiducial and total inclusive cross sections

Theoretical uncertainties can impact on the fiducial cross sections measurement, the determination of the correction factors and in particular, on the production mode fractions, which are based on the best available SM calculations and the background estimates.

In order to avoid model dependence, but taking into account existing constraints from measurements, the uncertainties on the production mode fractions are taken from the ATLAS-CMS combined couplings measurement [44]: 30%, 90% and 100% for the VBF, VH and $t\bar{t}H$ processes, are taken into account respectively.

The relative impact of these uncertainties on the correction and acceptance factors is at the level of 1% and 0.4% respectively.

The uncertainty on the expected ZZ^* background, evaluated by varying the QCD normalization and factorization scales varies with m_{ZZ^*} , from ± 3 to $\pm 5\%$.

The effect of the uncertainty on the PDF and α_S varies between ± 2 and $\pm 5\%$ and is estimated using the envelope of 52 eigenvectors of CT10nlo, and

two additional PDF sets, MSTW2008 and NNPDF3.0. The impact on the background estimates in the signal region is of the order of $2 - 5\%$. For the total cross section the impact of the theoretical uncertainties on the signal acceptance and the uncertainties on the Higgs boson branching fraction are also considered. to the branching ratio and amounts to 2.2% .

Theoretical uncertainties on event categorisation and EFT parameterization

The main source of theoretical uncertainty is given by the prediction of the ggF process in the different N_{jet} categories and the corresponding discriminant distributions: the ggF process is the major background in the 2-jet categories used to extract the VBF and VH cross sections measurements. The uncertainty on the gluon fusion cross section due to missing higher-order calculation terms is typically evaluated by varying the QCD renormalization (μ_R) and factorization (μ_F) scales. Therefore, the symmetrized difference in di-jet yield between the nominal and upward/downward scale variations gives the uncertainty on the cross section.

Therefore, when performing a jet bin-based analysis, an additional source of uncertainty must be considered which enters in the effect of the jet binning on the QCD perturbative uncertainty.

The uncertainties on the cross section prediction in inclusive N_{jet} selections are propagated to the exclusive jet bin requirements using the expected ggF fractions keeping track of the correlation of the migrations between exclusive jet bins.

The uncertainties on the shapes of the discriminants are those related to the BDTs used in the VH-hadronic and VBF 2-jet categories. These have been evaluated by taking the envelope between the QCD scale uncertainties applied to the MadGraph5_aMC@NLO (with the FxFx merging scheme) sample and the difference between this sample and the baseline Powheg simulation. The bin-by-bin uncertainties on the BDT score shapes given in Figure 5.31 for the ≥ 2 -jet VBF and VH BDTs show that the largest uncertainties are seen in the positive edge of the VBF BDT score distribution, where one would expect the most VBF-like behaviour, and the smallest concentration of ggF events. The remaining bins show an uncertainty generally of $10\text{-}20\%$, while the shape of the VH BDT is generally seen to have associated uncertainties of $\mathcal{O}(10\%)$.

For the 0- and 1-jet BDT discriminants the uncertainties have been evaluated by propagating the QCD and PDF uncertainties on the baseline sample and they have a negligible impact on the final measurement.

Additional uncertainties on the acceptance of the ggF process related to the QCD scale uncertainty, PDF and underlying event plus parton shower have also been included.

For the VH (with hadronic vector boson decays) and VBF production modes

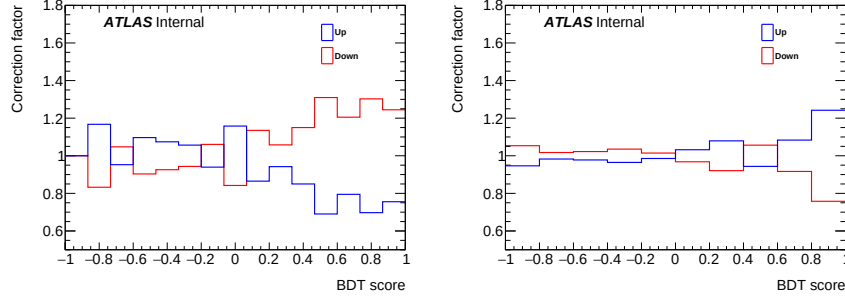


Figure 5.31: Mismodelling uncertainties derived from multiple polynomial fits to the BDT bin correction factors, and the FxFx scale variation uncertainties, for the VBF BDT (left) and the VH BDT (right).

the two leading jets are already present in the leading order matrix element so theoretical uncertainties are expected to be much smaller with respect to those from the ggF process; their systematics have been evaluated by varying QCD scales and applying the PDF uncertainties as for the ggF signal. The theoretical uncertainties on the dominant ZZ^* background are evaluated following the same procedure as for the inclusive cross section and, in addition, to evaluate possible migration between categories, the prediction between the baseline sample Powheg are compared with the predictions of the Sherpa2.1.1 generator which contains matrix element predictions up to three additional partons.

Due to the limited statistics for the Sherpa sample in the signal region, the systematic uncertainties are extracted over an enlarged mass range ($m_{4\ell} > 100 \text{ GeV}$). The fraction of events in the different reco-categories have been compared and the relative differences are used as systematic uncertainties: in propagating them to the results, the correlations between category migrations has been preserved. In addition, the yields in different jet bin categories have been compared to the data in the $m_{4\ell}$ region dominated by the ZZ^* background (above 200 GeV) and a good agreement between the Sherpa predictions and the data is found. The discriminant distributions have been also compared between Powheg and Sherpa and with the data in the high mass region (Figure 5.32), the low mass comparison between Powheg and Sherpa is also shown. Since the observed differences are rather small and given the large data statistical uncertainties, the systematic uncertainty associated to the discriminant shapes have been considered as negligible.

Concerning the search for BSM interactions, parameterized via the EFT Lagrangian terms, the theoretical uncertainties on the PDF set and the missing higher order QCD and EW corrections are in general assumed to factorize with respect to the new physics. The main sensitivity to the BSM couplings

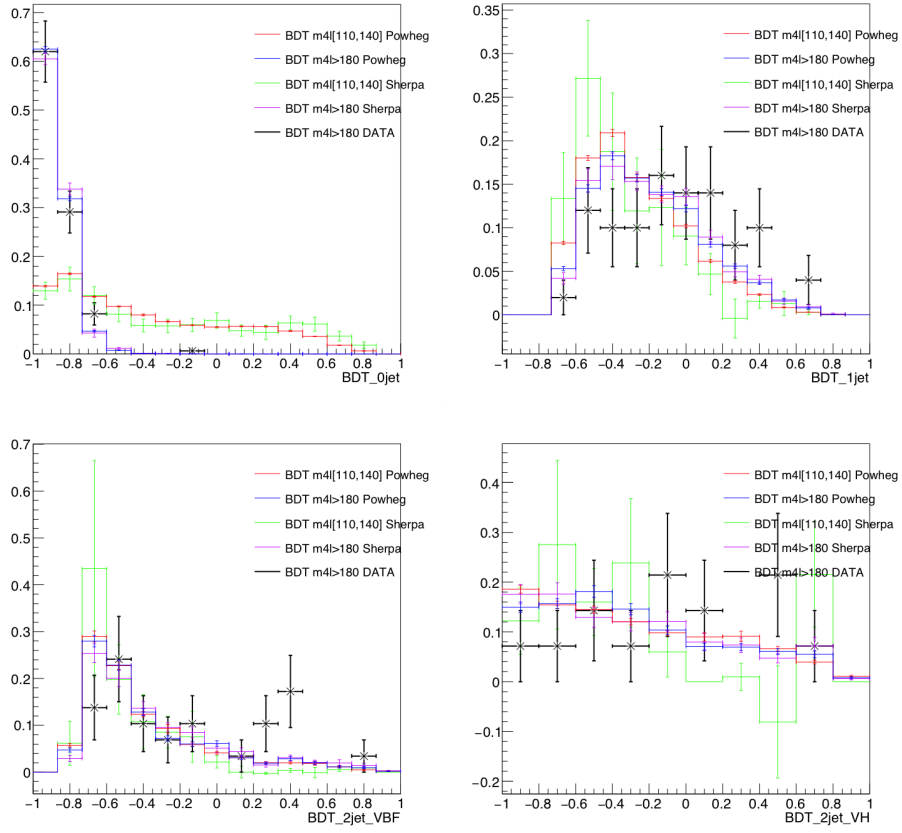


Figure 5.32: Normalized distributions of BDT discriminants for Powheg and Sherpa compared the data in the high mass region dominated by the ZZ^* background. The low mass comparison between Powheg and Sherpa is also shown.

under study (κ_{HVV} and $\kappa_{AVV} \cdot \sin\alpha$) comes from the VBF and VH production yields that are expected to scale as the fourth power of the BSM couplings.

Differences in k-factors between several BSM models and SM are shown to be in the range of 2 – 12% for both VBF and VH processes. The distributions of several kinematic quantities affecting the event categorization, like the jet transverse momenta and the di-jet invariant mass, are shown to receive higher order corrections that can differ, depending on the value of the BSM couplings, up to 20% from those computed for the SM process [53]. For this reason, in addition to the theoretical uncertainties applied to the different signals described above, a 30% uncertainty on the BSM signal acceptance in each category for the VH and VBF processes is also applied in order to cover the difference between LO and NLO calculations, the difference in k factor among SM and BSM models, and the error on the cross sections.

5.6 Results

5.6.1 Observed events

Observed distributions of the data corresponding to $L_{int} = 14.8 \text{ fb}^{-1}$ recorded at $\sqrt{s} = 13$ TeV are shown superimposed to the MC expectations for the 0-jet, 1-jet, 2-jet VBF-enriched, and 2-jet VH-Hadronic-enriched categories in Figure 5.33.

The expected and observed yields in each category for $118 < m_{4\ell} < 129$ GeV are summarized in Table 5.7. The expected and observed signal significance

Table 5.7: Expected and observed yields in the 0-jet, 1-jet, 2-jet with $m_{jj} > 120$ GeV (*VBF-enriched*), 2-jet with $m_{jj} < 120$ GeV (*VH-enriched*) and VH-leptonic categories. The yields are given for the different production modes, assuming $m_H = 125$ GeV, the ZZ^* and reducible background for 14.8 fb^{-1} at $\sqrt{s} = 13$ TeV. The estimates are given for the $m_{4\ell}$ mass range 118–129 GeV.

Analysis category	Signal				Background		Total expected	Observed
	$ggF + b\bar{b}H + t\bar{t}H$	VBF	WH	ZH	ZZ^*	$Z + \text{jets}, t\bar{t}$		
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07	8.5 ± 2.4	12
2-jet VH enriched	1.1 ± 0.5	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009	0.166 ± 0.035	0.088 ± 0.011	1.6 ± 0.5	2
2-jet VBF enriched	1.9 ± 0.9	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005	0.22 ± 0.05	0.24 ± 0.11	3.4 ± 0.9	9
VH-leptonic	0.055 ± 0.004	0.00217 ± 0.00015	0.067 ± 0.004	0.0105 ± 0.0006	0.0156 ± 0.0015	0.012 ± 0.010	0.163 ± 0.012	0
Total	20 ± 4	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027	8.2 ± 0.9	1.62 ± 0.07	32 ± 4	44

values for each process are also summarized in Table 5.8.

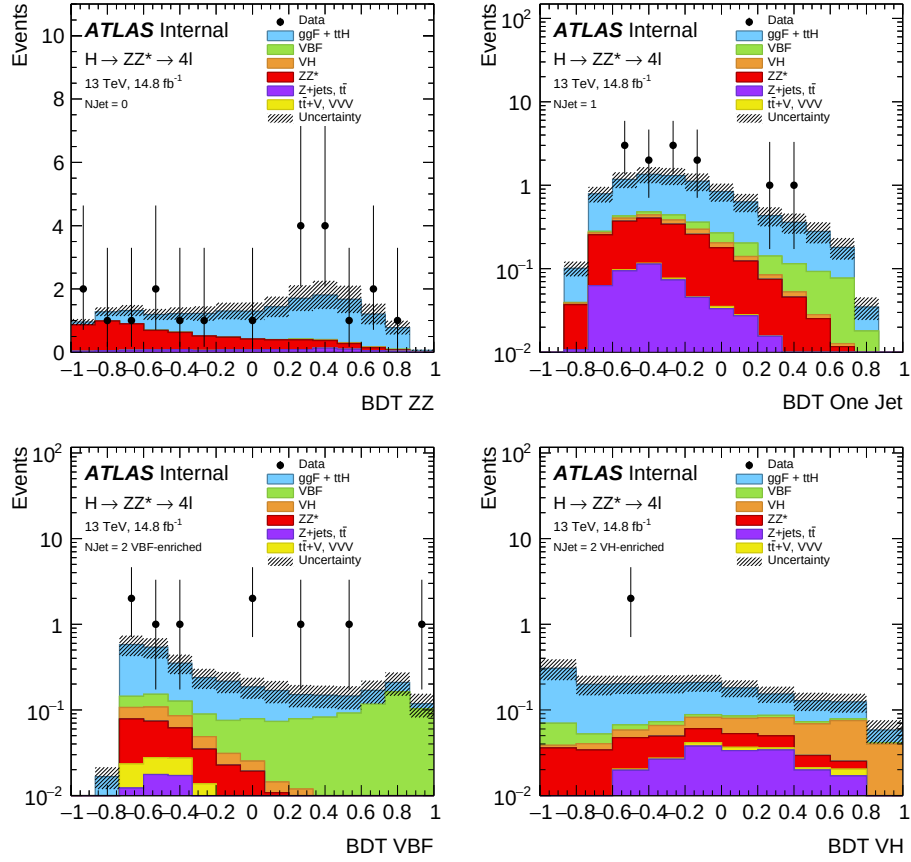


Figure 5.33: Distributions of BDT discriminants for data superimposed on MC normalized to the SM prediction for $L_{int} = 14.8 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$. From left to right are distributions for the 0-jet, 1-jet, 2-jet VBF-enriched, and 2-jet VH-Hadronic-enriched categories.

Table 5.8: The expected and observed signal significance of the summed ggH, bbH and ttH processes, VBF, and VH process for 14.8 fb^{-1} at $\sqrt{s} = 13$ TeV.

Production process	ggH+bbH+ttH	VBF	VH
expected with syst. / σ	3.9	0.92	0.40
observed with syst. / σ	4.5	2.2	0

5.6.2 Cross section per production mode

The total production cross section of ggH, VBF and VH process, multiplied by the branching ratio of Higgs decays to two Z bosons have been measured. In doing this, the ggH contribution has been rescaled to take into account also for the bbH and ttH ones, following the SM predictions.

The expected and observed measurements are obtained from NLL scans shown in Figure 5.35 and the expected and observed results are summarized in Tables 5.9 and 5.10, respectively.

Table 5.9: The expected cross section per production mode results ($(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VH}^{ZZ}$), for 14.8 fb^{-1} at $\sqrt{s} = 13$ TeV.

Production process	Expected (with syst., pb)
$(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$	$1.31^{+0.44}_{-0.39}$
$(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$	$0.100^{+0.183}$
$(\sigma \times \mathcal{BR})_{VH}^{ZZ}$	$0.059^{+0.247}$

Table 5.10: The expected and observed cross section per production mode results ($(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VH}^{ZZ}$), for 14.8 fb^{-1} at $\sqrt{s} = 13$ TeV.

Production process	Expected (pb)	Observed (no syst., pb)	Observed (with syst., pb)
$(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$	1.31 ± 0.07	$1.80^{+0.47}_{-0.42}$	$1.80^{+0.49}_{-0.44}$
$(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$	0.100 ± 0.003	$0.37^{+0.27}_{-0.20}$	$0.37^{+0.28}_{-0.21}$
$(\sigma \times \mathcal{BR})_{VH}^{ZZ}$	0.059 ± 0.002	$0^{+0.15}$	$0^{+0.15}$

The compatibility of the measurement with the SM expectation is evaluated to be 1.1σ for the combined ggH, bbH and ttH process, and 1.4σ for the VBF process, from the NLL scans of the corresponding process.

A two dimensional likelihood scan of the $(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$ and $(\sigma \times \mathcal{BR})_{VBF+VH}^{ZZ}$ is shown in Figure 5.36, and the observed result is within 2σ deviation from the SM.

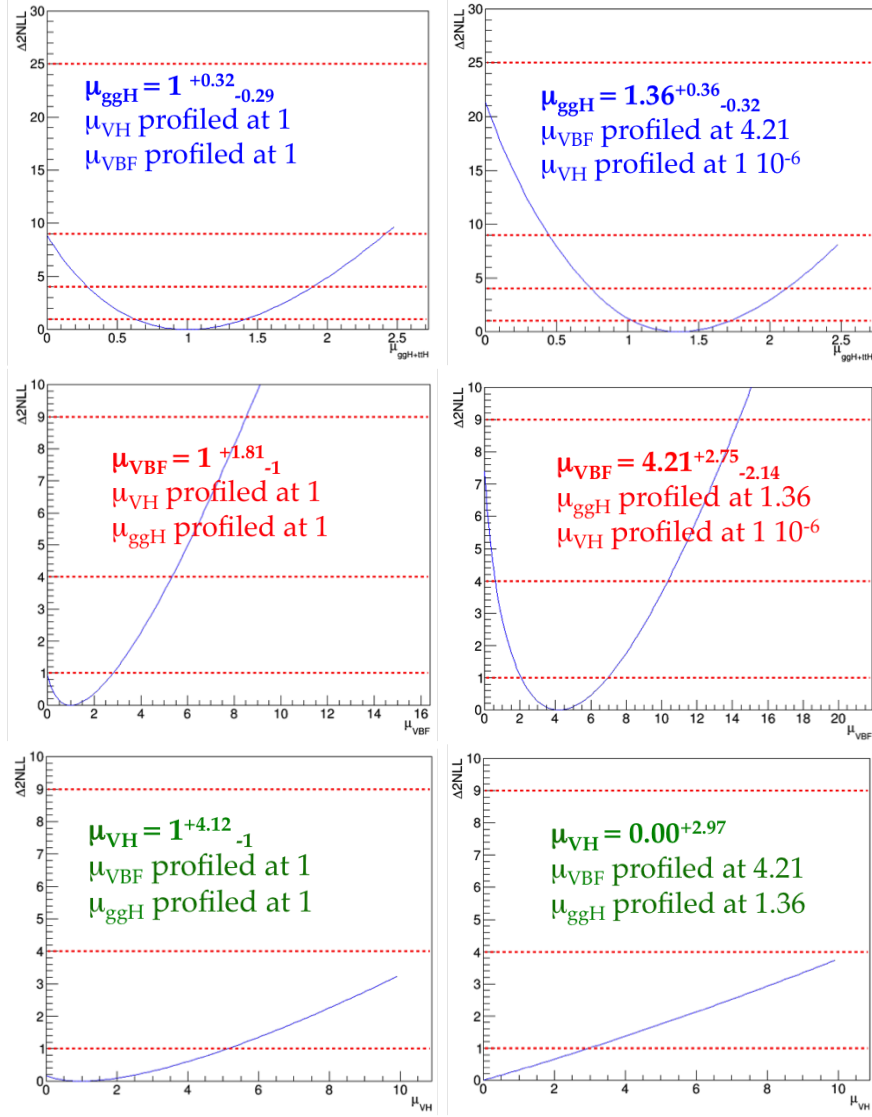


Figure 5.34: NLL scan results for $L_{\text{int}} = 14.8 \text{ fb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV}$ data with a minimal set of systematic uncertainties expressed as a signal strength with respect to the SM values of the cross sections.

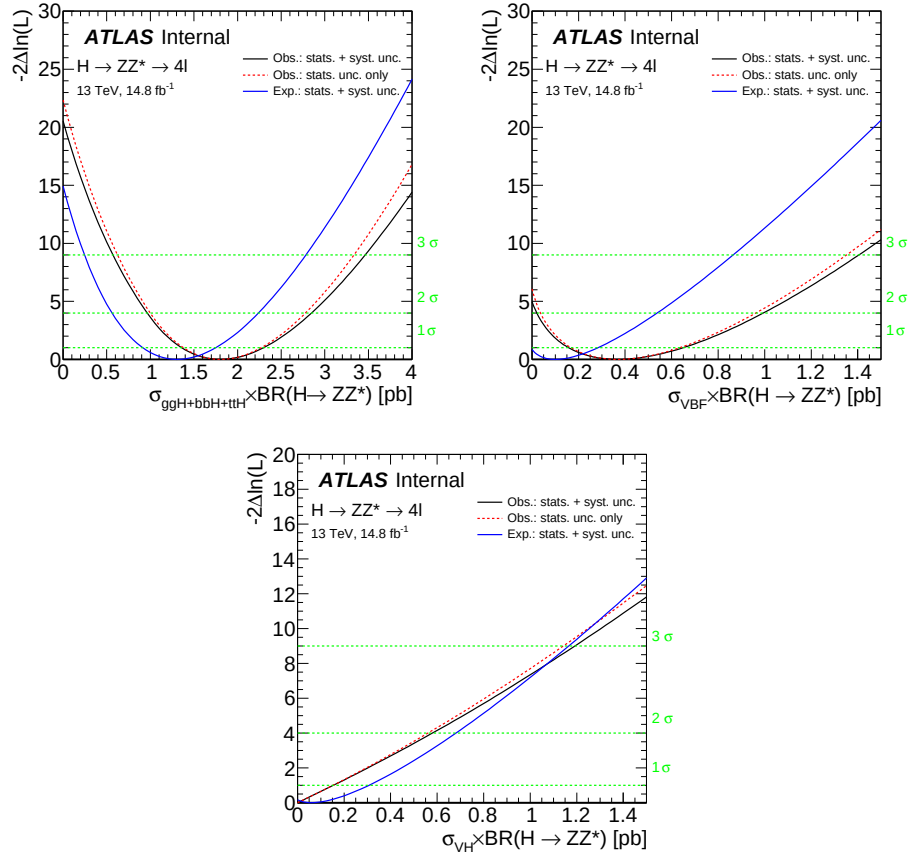


Figure 5.35: NLL scan results for $L_{int} = 14.8 \text{ fb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV}$ data.

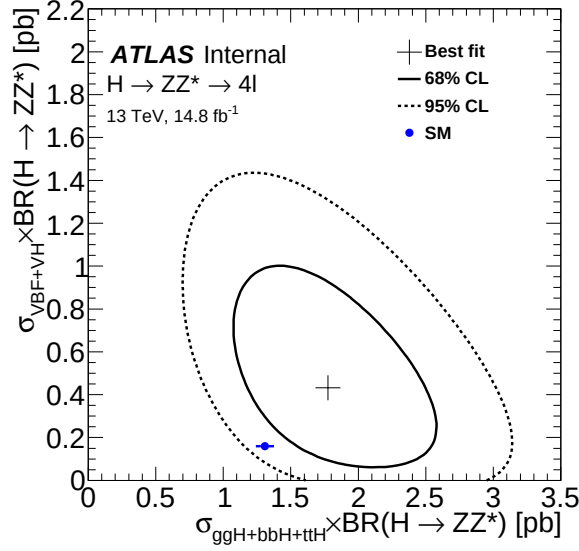


Figure 5.36: 2D likelihood scan of the $(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$ and $(\sigma \times \mathcal{BR})_{VBF+VH}^{ZZ}$, together with SM expectations

5.6.3 Interpretation in the κ framework

The result of the simplified template cross sections measurement has been also interpreted in the κ framework performing a 2D likelihood scan of the κ_V and κ_F shown in Figure 5.37 being κ_V and κ_F respectively the coupling of the Higgs boson to vector bosons and fermions (as described in Chapter 1). The results show an agreement within 2σ with respect to the SM prediction.

5.6.4 Higgs EFT analysis

The expected results for the tensor coupling analysis are obtained using an Asimov dataset built from Standard Model events. The likelihood expected distribution of Figure 5.38 (right) is symmetric since the cross section scales at the same rate for negative and positive values of κ_{AVV} ; a small asymmetry is therefore seen due to the difference in the categorization among positive and negative values of κ_{AVV} .

Concerning κ_{HVV} (Figure 5.38 left), for negative values, an interference between SM and BSM contributions, which is the cause of the asymmetry observed here in the scan of the Likelihood function and already described in Section 5.4.3.

In this studies, the SM coupling have been fixed to the SM prediction ($\kappa_{SM} = 1$), therefore, every deviation with respect to the SM prediction

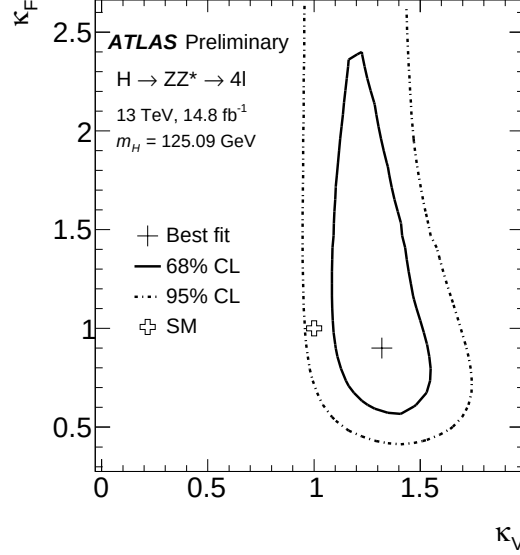


Figure 5.37: 2D likelihood scan of the κ_V and κ_F .

is interpreted as coming from BSM contributions (no global scaling is taken into account for the SM contribution).

Figure 5.38 shows the expected and observed results for the tensor coupling analysis.

In both distributions the minimum is shifted with respect to the pure SM case, with observed minima being $\kappa_{AVV} \times \sin(\alpha) = 5$. and $\kappa_{HVV} = 4.51$.

Although the likelihood minima are not at zero (which would indicate purely SM behaviour), reasonable compatibility with the SM ($\sim 2\sigma$ -level) is observed.

Due to a small data excess in the ≥ 2 -jet category (the most sensitive for the tensor coupling analysis), the observed limit of $\kappa_{AVV} \times \sin(\alpha)$ (in which the mixing sample always has a larger cross section than the SM case) is worse than the expected limit.

In the κ_{HVV} analysis, due to the previously-described interference term, negative values of κ_{HVV} are disfavoured.

In the case of positive values of κ_{HVV} , the cross section is expected to be larger than the SM case. Therefore, due to the excess of data observed in the ≥ 2 -jet category, positive values of $\kappa_{AVV} \times \sin(\alpha)$ are favoured. Table 5.11 shows a comparison between the observed and expected limits at 95% CL.

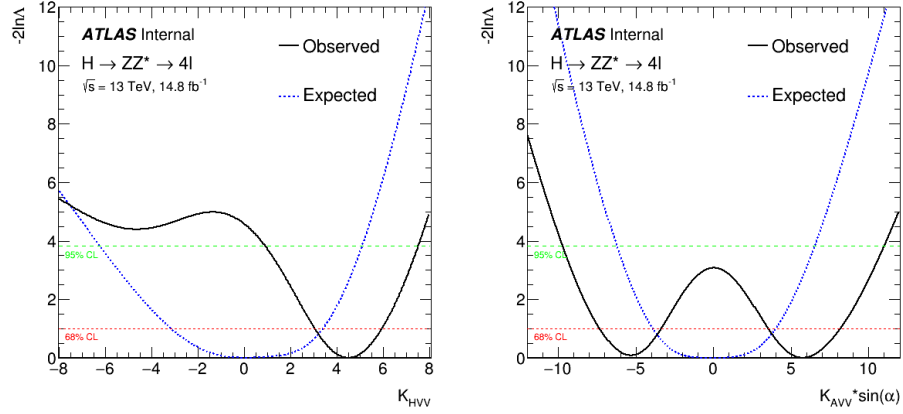


Figure 5.38: Observed (black) and expected (blue) results for the κ_{HVV} (left) and κ_{AVV} (right) analysis of the tensor coupling structure of the Higgs Boson.

Table 5.11: Comparison among the Observed and Expected exclusion limits with the Run2 dataset.

Expected not excluded range at 95% CL	κ_{HVV}	$\kappa_{AVV} \times \sin(\alpha)$
Run 2 dataset	$[-6.25, 5.05]$	$[-6.25, 6.5]$
Observed not excluded range at 95% CL	κ_{HVV}	$\kappa_{AVV} \times \sin(\alpha)$
Run 2 dataset	$[0.9, 7.45]$	$[-9.7, 11.0]$

Chapter 6

From the k-framework to the EFT approach: sensitivity study on the parametrization of the decay amplitude in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel

A phenomenological study is presented in the context of the Effective Field Theory (EFT) approach to the Higgs Physics: a set of Pseudo Observables (POs) characterizing the properties of the Higgs decays are then defined in generic extensions of the SM assuming no new particles below the Higgs mass.

The expected sensitivity with the next LHC runs to the EFT parameters has been evaluated using the measurement of the double differential cross section in the invariant masses of the di-leptons systems for the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel.

6.1 Introduction

The main idea that lies behind the work is to present a sensitivity study based on the EFT parametrization proposed by G. Isidori, A. Greljo, D. Marzocca and M. González- Alonso [28]. This work has been motivated by the Higgs discovery, and it relies on the hypothesis that $h(125)$ is a spin zero particle and that there is no new particle with mass below (or around) $m_H \sim 125$ GeV able to provide significant kinematical distortions of the Higgs decays to SM particles. In this regime where, the Effective Field Theory (EFT) approach is applicable, no further assumption have been done in order to specify if the $h(125)$ state is part of an $SU(2)_L$ doublet (the so-

called linear EFT approach), or if it is the mass eigenstate resulting from a more complicated symmetry breaking sector (the so-called non-linear EFT approach). Global symmetry hypotheses such as lepton-universality, $\mathcal{CP}$ invariance and custodial symmetry are not imposed and can be tested from data.

The only key assumption is to neglect terms in the decay amplitudes that receive non-vanishing tree-level contributions from local operators with dimension greater than six ($D > 6$).

Under such general assumptions it is possible to define a limited set of POs that can be directly determined from experimental data on Higgs physics and that encode all possible New Physics effects.

The aim of the Higgs POs is to characterize the properties of $h(125)$ in generic BSM (with heavy New Physics) encoding the experimental results in terms of a limited set of observables of easy theoretical interpretation. Typical values of the $Z \rightarrow \bar{\ell}\ell$ contact terms in EFT theories goes around 0.2.

6.2 Higgs decay to four fermions

The $h \rightarrow 4f$ amplitudes are particularly interesting since they allow to investigate the effective hW^+w^- and hZZ interaction terms, which cannot be probed on-shell. Extracting the kinematical structure of the decay from data will allow both to determine the effective coupling of the h to all the SM gauge bosons, and also to investigate possible its couplings to new massive states (i.e. New Physics).

The Higgs POs are defined from a momentum expansion of the on-shell electro-weak Higgs decay amplitudes around the physical poles due to the exchange of SM electro-weak gauge bosons (as long as $D > 6$ operators are neglected).

The approach that will be shown is a general EFT approach, and it reflects the importance of investigating the kinematics of the events and the total rate at the same time.

To do so, the decay amplitude $h \rightarrow 2e2\mu$, defined as a function of 5 pseudo-observables, has been used to extract the parameter values via a binned Likelihood fit: several configurations have been analyzed reducing the number of independent POs following from the hypotheses of lepton-universality, $\mathcal{CP}$ invariance, custodial symmetry, and linearly realized electro-weak symmetry breaking.

Results will be shown for the statistics available from the LHC RunI and projections will be given for $100fb^{-1}$ and $300fb^{-1}$ at 13 TeV for the LHC Run2.

6.3 Decay amplitude and extraction of the parameters

In order to extract the contact terms values it is necessary to study the double differential decay distribution in q_1^2 and q_2^2 ; with $q_1 = m_{12}$ and $q_2 = m_{34}$.

This work will focus only on the Higgs boson decay to pairs of muons and electrons, which is a particularly clean process with non-trivial kinematics. In deriving the fully analytic expression of the double differential decay distribution in each lepton pair's invariant mass after integrating over the angular variables, one can write the most generic expression of the decay amplitude of an on-shell Higgs boson in a $2e2\mu$ final state as a function of POs (namely $k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R}, \epsilon_{ZZ}^{\mathcal{CP}}, \epsilon_{Z\gamma}^{\mathcal{CP}}, \epsilon_{\gamma\gamma}^{\mathcal{CP}}$):

$$A = i \frac{2m_Z^2}{v_F} \Sigma_{e=e_L, e_R} \Sigma_{\mu=\mu_L, \mu_R} (\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta \mu) \times [F_1^{e\mu}(q_1^2, q_2^2) g^{\alpha\beta} + F_3^{e\mu}(q_1^2, q_2^2) \frac{q_1 q_2 g^{\alpha\beta} - q_1^\alpha q_2^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2, q_2^2) \frac{\epsilon^{\alpha\beta\rho\sigma} q_{2\rho} q_{1\sigma}}{m_Z^2}]$$

The form factors $F_1^{e\mu}(q_1^2, q_2^2)$, $F_3^{e\mu}(q_1^2, q_2^2)$ and $F_4^{e\mu}(q_1^2, q_2^2)$ have the following expressions:

$$\begin{aligned} F_1^{ff'}(q_1^2, q_2^2) &= k_{ZZ} \frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2} \frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2} \frac{g_Z^f}{P_Z(q_1^2)} \\ F_3^{ff'}(q_1^2, q_2^2) &= \epsilon_{ZZ} \frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma} \left(\frac{e Q_{f'} g_Z^f}{q_2^2 P_Z(q_1^2)} + \frac{e Q_f g_Z^{f'}}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma} \frac{e^2 Q_f Q_{f'}}{q_1^2 q_2^2} \\ F_4^{ff'}(q_1^2, q_2^2) &= \epsilon_{ZZ}^{\mathcal{CP}} \frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2) P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\mathcal{CP}} \left(\frac{e Q_{f'} g_Z^f}{q_2^2 P_Z(q_1^2)} + \frac{e Q_f g_Z^{f'}}{q_1^2 P_Z(q_2^2)} \right) + \epsilon_{\gamma\gamma}^{\mathcal{CP}} \frac{e^2 Q_f Q_{f'}}{q_1^2 q_2^2} \end{aligned}$$

where g_Z^f are the effective couplings and $P_Z(q^2) = q^2 - m_Z^2 + im_Z \Gamma_Z$. Imposing the $\mathcal{CP}$ invariance, and recalling the Higgs boson to be a $\mathcal{CP}$ -even state, the term $F_4^{e\mu}(q_1^2, q_2^2)$ cancels out and the most interesting effects can be seen in the $F_1^{e\mu}(q_1^2, q_2^2)$ term. Following these series of simplifications, at the end there will be 5 POs left: $k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R}$ which represent the coupling to the hZZ vertex and the contact terms of the Z boson with leptons respectively.

The double differential decay distribution in q_1 and q_2 leads to a quadratic polynomial function in $k = (k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R})^T$, therefore, the decay amplitude can be written as a function of the POs as follows:

$$d^2\Gamma_{H \rightarrow 2e2\mu}/dm_{12}dm_{34} = \Sigma_{j \geq i} A_{ij} k_i k_j$$

where m_{12} and m_{34} are the invariant masses of the $2e$ and 2μ respectively. Figure 6.1 shows the 2-dimensional function generated with an Asimov data

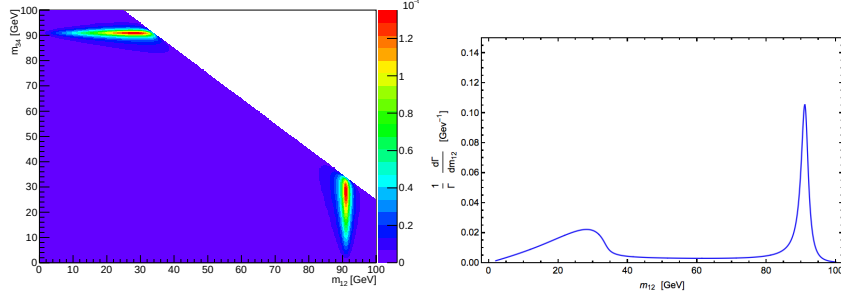


Figure 6.1: (left) Two dimensional function generated with parameters set to SM values: $(k_{ZZ}, \epsilon_{ZeL}, \epsilon_{Z\mu L}, \epsilon_{ZeR}, \epsilon_{Z\mu R}) = (1, 0, 0, 0, 0)$. (right) The projection along m_{12} is shown, integrating over m_{34} .

set (10k events extracted and normalized to the statistics available in Run1 by ATLAS and CMS) at SM values and the projection along m_{12} while integrating over m_{34} . Figure 6.2 shows the $d\Gamma_{H \rightarrow 2e2\mu}/dm_{12}$ distribution integrated over m_{34} for different values of the POs, showing their impact on the differential distribution.

It is important to stress here, that the k_{ZZ} differs from the usual signal strength, as reported by the ATLAS and CMS Collaborations, since the latter is linked to a well known kinematical distribution (the SM-like one).

6.4 Results

The sensitivity on the POs previously described has been provided using a profiled likelihood ratio test: New Physics hypothesis have been tested with respect to pure SM hypothesis. Minuit [26] has been used for the likelihood minimization.

The extraction of the events have been performed using an Asimov dataset build starting from the double differential rate. The expected number of events have been normalized to the statistics recorded by both ATLAS and CMS in the LHC Run1: ~ 15 events in the $2e2\mu$ channel in the mass window $[120 - 130]$ GeV [27, 39].

A binned Likelihood then has been built and a scan over the parameter of interest as been performed; studies were carried out following several configurations and will be given for the statistics observed available in the LHC Run1 (ATLAS + CMS); in addition, projections for $100fb^{-1}$ and $300fb^{-1}$ at 13 TeV for the Run2 of LHC will be given accordingly.

In doing this, the number of events expected at 13 TeV have been obtained by rescaling number of events per fb^{-1} by the ratio of the total production cross section at 13 TeV with respect to the 8 TeV center of mass energy case.

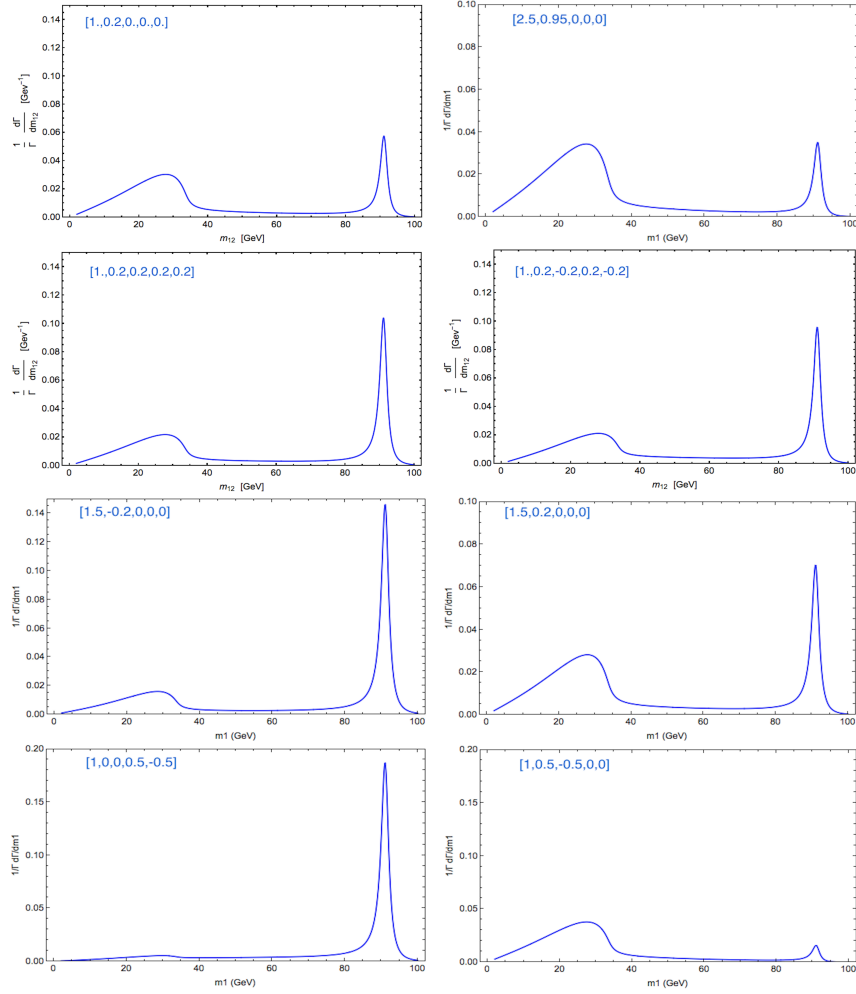


Figure 6.2: The $d\Gamma_{H \rightarrow 2e2\mu}/dm_{12}$ distribution for different values of the POs, showing their impact on the differential distribution.

In this study, efficiency and acceptance factors have been neglected at the moment and systematics are not included at the moment.

Different combinations of the parameters have been studied since they were showing interesting features in investigating possible deviations from the SM values of the POs. In order to do so, some of them have been fixed to their SM values, while fitting the others.

The most interesting cases found are reported in the following:

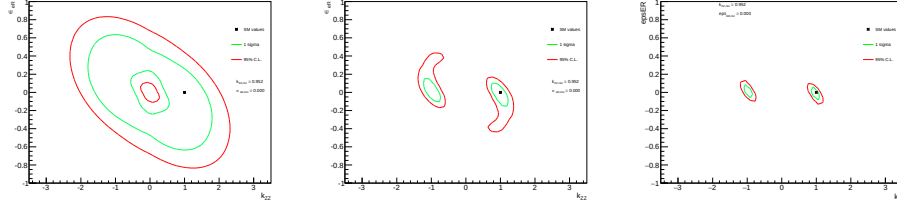
- A: scan over (k_{ZZ}, ϵ_{ZeR}) , fixing $\epsilon_{Z\mu L}, \epsilon_{ZeL}$ and $\epsilon_{Z\mu R}$ to their SM expectations ($\epsilon_X = 0$). This test is interesting in order to give an estimate of the sensitivity on the contact terms which have never been considered before.
- B: scan over $(k_{ZZ}, \epsilon_{ZLepR})$, being $\epsilon_{ZLepL} = 2 \cdot \epsilon_{ZLepR}$ and $\epsilon_{Z\mu X} = \epsilon_{ZeX}$. In this case the LFU is imposed and the assumption of the Higgs being part of an $SU(2)_L$ doublet is made, therefore comes the relation between ϵ_{ZLepL} and ϵ_{ZLepR} .
- C: scan over $(\epsilon_{ZLepR}, \epsilon_{ZLepL})$, fixing $k_{ZZ} = 1$ (SM) and imposing LFU, i.e. $\epsilon_{ZeX} = \epsilon_{Z\mu X}$. This case is mainly made to test LFU.
- D: scan over $(\epsilon_{ZeR}, \epsilon_{Z\mu R})$, fixing $k_{ZZ} = 1$ (SM) and assuming an axial coupling of a Z' with a couple of leptons, i.e. $\epsilon_{ZeR} = -\epsilon_{ZeL}$ and $\epsilon_{Z\mu R} = -\epsilon_{Z\mu L}$.
- E: scan over $(\epsilon_{ZeR}, \epsilon_{Z\mu R})$, fixing k_{ZZ} and assuming a vectorial coupling of a Z' with a couple of leptons, i.e. $\epsilon_{ZeR} = \epsilon_{ZeL}$ and $\epsilon_{Z\mu R} = \epsilon_{Z\mu L}$.

In the last two cases, the contact terms are assumed to be different for muons and electrons, reflecting the case of a flavor symmetry violation.

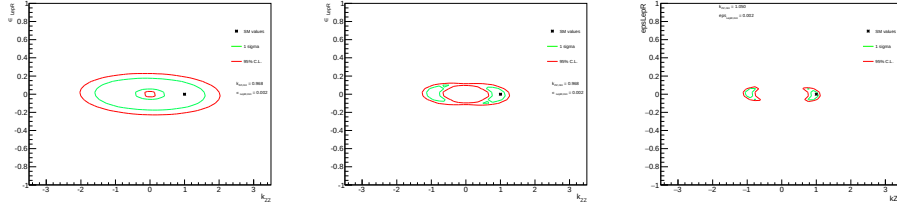
From the plots shown in Figures 6.3 and 6.4, it can be seen that the sensitivity on the contact term with the statistics available from Run1 is not sufficient to exclude some EFTs, but $100fb^{-1}$ at 13 TeV would be enough to start discriminating between EFTs (typical values of the contact terms in EFTs goes around 0.2).

The framework of the Higgs Pseudo Observables, therefore, can capture all the physics accessible in Higgs decays if no new light state is coupled to the Higgs boson and can be efficiently used to test possible New Physics effects including information both from shapes and normalization of the double differential distribution.

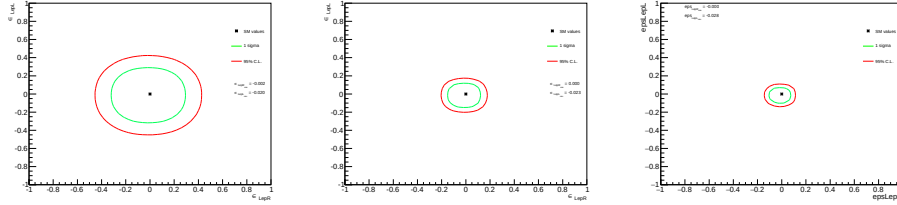
Limits of this test are represented by the fact that no background has been included, nor detector efficiency and acceptance factors.



(a) Case A, Run1 statistics. (b) Case A, projections for $100fb^{-1}$ at 13 TeV. (c) Case A, projections for $300fb^{-1}$ at 13 TeV.



(d) Case B, Run1 statistics. (e) Case B, projections for $100fb^{-1}$ at 13 TeV. (f) Case B, projections for $300fb^{-1}$ at 13 TeV.



(g) Case C, Run1 statistics. (h) Case C, projections for $100fb^{-1}$ at 13 TeV. (i) Case C, projections for $300fb^{-1}$ at 13 TeV.

Figure 6.3: Each row corresponds to the tests mentioned in the text: (top to the bottom) cases A, B, and C. The left column reflects what expected for the statistics available in the LHC Run1, the middle and the right columns shows what is expected for $100fb^{-1}$ and $300fb^{-1}$ respectively at 13 TeV. The green contour and the red contour reflects respectively the 1σ and the 95% C.L. . The value of the POs obtained from the fit are also shown in each plot.

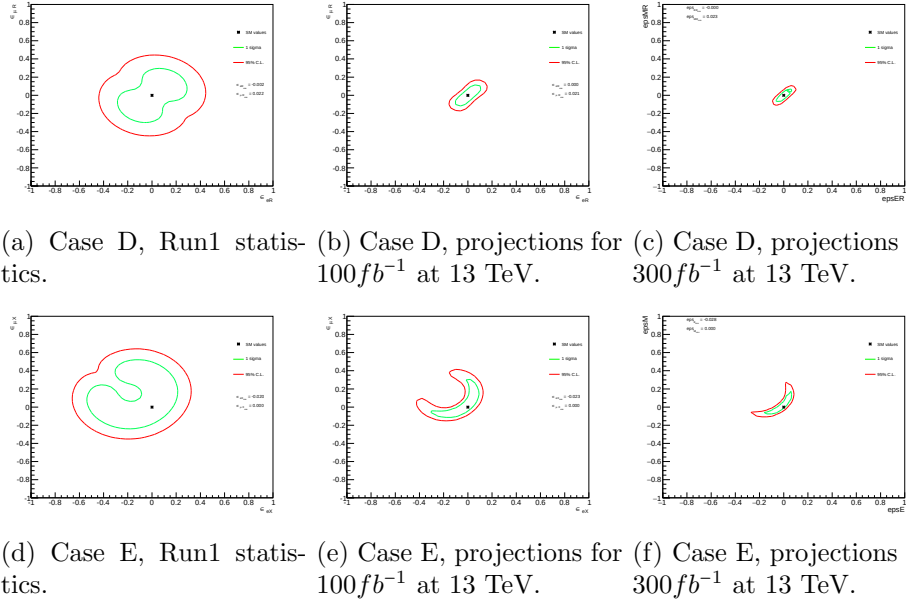


Figure 6.4: Each row corresponds to the tests mentioned in the text: (top to the bottom) cases D and E. The left column reflects what expected for the statistics available in the LHC Run1, the middle and the right columns shows what is expected for $100fb^{-1}$ and $300fb^{-1}$ respectively at 13 TeV. The green contour and the red contour reflects respectively the 1σ and the 95% C.L. . The value of the POs obtained from the fit are also shown in each plot.

Conclusions

The thesis's work is focused on the analysis performed to study the Higgs-like resonance properties in the decay channel $H \rightarrow ZZ^* \rightarrow 4\ell$.

The results presented in this thesis are obtained using the 2012 and 2015 proton-proton collision data respectively of 20.3 fb^{-1} and 14.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$ recorded with the ATLAS detector at LHC.

The first measurements of the fiducial inclusive and differential cross sections are described ¹. Particular attention is posed on the dependencies of the cross sections on the Higgs boson spin/ $\mathcal{CP}$ quantum numbers, perturbative QCD predictions and parton distribution functions (PDFs). The cross section dependence on the transverse momentum of the four lepton system ($p_{T,4\ell}$) has been measured to test spin/ $\mathcal{CP}$ and perturbative QCD effects; the rapidity ($|y|_{4\ell}$) of the four lepton system shows sensitivity to QCD radiative corrections and PDFs; the invariant mass of the sub-leading lepton pair (m_{34}) and the angle between the on-shell Z and the beam axis ($\cos\theta^*$) are sensitive to spin/ $\mathcal{CP}$ and higher order operators in the Lagrangian structure of the Higgs boson interactions; while the cross section distributions in jet variables (N_{jets} , transverse momentum of the leading jet $p_{T,jet1}$) is sensitive to QCD radiation effects. Accuracies ranging between 20–50% are obtained with the 20.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ data set. Table 1 shows the χ^2 probability of the tests.

Results have shown no significant deviations with respect to the SM predictions within the errors, which are dominated by statistics. In this sense, more data are required to gain sensitivity in this measurements: the expected improvement at the end of Run2 will be of about a factor 5 with respect to the presented results.

Additional information on the Higgs properties can be obtained studying the coupling of the Higgs boson to the SM particles. In particular, the first attempt in categorizing the $H \rightarrow 4\ell$ events in production-mode enriched categories has been performed with the 14.8 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ data set.

The results presented in this thesis have been officially presented for the first time at ICHEP 2016 ².

¹Presentation for the Open Reading: indico.cern.ch/event/327318/ (G.Mancini)

²Presentation for the Approval: indico.cern.ch/event/558379/ (G.Mancini)

Variable	χ^2 Compatibility (%)		
	Powheg	HRes2.0	MinLo
$p_{T,H}$	30	16	23
$ y $	37	36	45
m_{34}	48	-	60
$ \cos\theta^* $	35	-	45
N_{jets}	37	-	28
$p_{T,jet1}$	33	-	26

Table 1: Compatibility test with the SM hypothesis using the Powheg, HRes2.0 and MinLo calculation. The reported values are the probabilities of observing a distribution with a χ^2 greater than or equal to the one observed.

Table 2 presents the results obtained for the cross sections per production process in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel. Results show compatibility

Table 2: The SM expected and observed cross sections per production mode ($(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$, $(\sigma \times \mathcal{BR})_{VH}^{ZZ}$) obtained with the $14.8fb^{-1}$ at $\sqrt{s} = 13$ TeV data set.

Production process	SM Expected [pb]	Observed [pb]
$(\sigma \times \mathcal{BR})_{ggH+bbH+ttH}^{ZZ}$	1.31 ± 0.07	$1.80^{+0.49}_{-0.44}$
$(\sigma \times \mathcal{BR})_{VBF}^{ZZ}$	0.100 ± 0.003	$0.37^{+0.28}_{-0.21}$
$(\sigma \times \mathcal{BR})_{VH}^{ZZ}$	0.059 ± 0.002	$0^{+0.15}$

with the SM within the errors. An interpretation of the results has been given in terms of coupling of the Higgs boson to vector bosons and fermions (within the so called "kappa" framework): results show consistency with the SM within 2σ .

This particular categorization has also shown good sensitivity in studying BSM contribution to the HVV interaction vertex; therefore studies have been performed to investigate possible BSM contribution to the SM Lagrangian, specifically, $\mathcal{CP}$ -odd ($(\kappa_{AVV} \times \sin(\alpha))/\Lambda$ effective coupling) and $\mathcal{CP}$ -even (κ_{HVV}/Λ effective coupling) BSM contributions to the observed Higgs boson production and decay rates have been tested. Limits on the corresponding BSM tensor couplings have been derived. The derived allowed ranges at 95% C.L. are presented in Table 3. Among the years after the discovery of the Higgs boson, studies aiming for measuring its property have been widely carried out.

Statistical significance still limits our measurements and we are looking forward to analyze new data in the near future to combine information from shape distributions and rates in a more coherent interpretation which correctly takes into account both. A first study of the potentiality of this

Table 3: The derived allowed ranges at 95% C.L. with the Run2 data set.

	Allowed range at 95% C.L. [$1/TeV$]
Test on the effective coupling of a BSM scalar operator $\left(\frac{\kappa_{HVV}}{\Lambda}\right)$	[0.9, 7.45]
Test on the effective coupling of a BSM pseudo-scalar operator $\left(\frac{\kappa_{AVV} \times \sin(\alpha)}{\Lambda}\right)$	[-9.7, 11.0]

method is presented using Pseudo Observables in a general EFT framework: results show that already at the end of Run2 we will have sufficient statistical power to exclude possible BSM theories constraining the contact terms with relative uncertainties at a few percent level.

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