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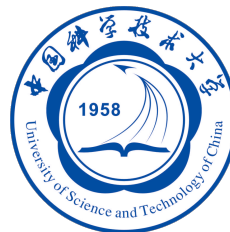
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**Mesure de l'efficacité d'identification des jets de
quarks b et observation des desintegrations du boson
de Higgs en deux quarks b avec le detecteur ATLAS**

Dirigée par Yanwen Liu et Giovanni Marchiori

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B-tagging Calibration and Observation of Higgs Boson Decays to a pair of bottom quarks with the ATLAS Detector

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Abstract

This thesis firstly describes a measurement of the b -jet tagging efficiency with a tag-and-probe method using data recorded by the ATLAS detector in 2015 and 2016. The efficiency measurement method, the object selection, the event and probe jet selection, the evaluation of the statistical and systematic uncertainties, and the final results are discussed. The b -tagging efficiencies have been measured as a function of the jet transverse momentum, pseudorapidity and of the average number of pile-up collisions. The efficiencies measured in data have been compared to those predicted from simulation, and simulation-to-data efficiency scale factors have been determined. The efficiency scale factors are close to unity, with total uncertainty ranging between 2% and 12%.

The second part of this thesis focuses on the search for the decays of the Standard Model (SM) Higgs boson to bottom quarks in the associated production mode with vector bosons. Two measurements have been performed and are described here: the first one is based on 36.1 fb^{-1} of 13 TeV pp collisions recorded by ATLAS during the LHC Run-2 until 2016; the second one includes the additional 44 fb^{-1} of 13 TeV pp collisions recorded in 2017.

For the study based on 36 fb^{-1} of data, the object reconstruction, event selection and classification, the techniques to discriminate the signal from the background, the main background and their modelling, the signal properties and the interpretation of results are discussed. For the study based on 80 fb^{-1} data, the main difference from the previous study are highlighted.

Both results provide a strong evidence of the VH , $H \rightarrow b\bar{b}$ process, with statistical significances of 3.5 and 4.9 standard deviations, respectively. The signal strength, defined as the ratio between the measured cross section times branching ratio and the SM prediction, is measured with the 2015–2017 dataset to be $\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16$ (stat.) $^{+0.21}_{-0.19}$ (syst.), indicating good agreement with the SM. The combination of the VH , $H \rightarrow b\bar{b}$ results based on 80 fb^{-1} of 13 TeV collisions with the results of the same analysis performed on data collected at lower (7 and 8 TeV) centre-of-mass energies in 2011 and 2012, and with those of the searches of $H \rightarrow b\bar{b}$ decays in other Higgs boson production modes (vector-boson fusion, associated production with a top-quark pair) have led to the observation of the $H \rightarrow b\bar{b}$ decay with a significance of 5.4 standard deviations, and to a measurement of the signal strength $\mu^{bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12$ (stat.) $^{+0.16}_{-0.15}$ (syst.). A combination of the results of the VH , $H \rightarrow b\bar{b}$ results based on 80 fb^{-1} of 13 TeV collisions with the results of searches for the same production mode on the same amount of data in the diphoton and $ZZ^* \rightarrow 4\ell$ Higgs boson final states has led to the observation of VH production with a significance of 5.3 standard deviations, and to a measurement of the signal strength $\mu^{VH} = 1.13^{+0.24}_{-0.23} = 1.13 \pm 0.15$ (stat.) $^{+0.18}_{-0.17}$ (syst.), in good agreement with the SM.

Keywords: LHC; ATLAS experiment; Higgs boson; VH associated production; simplified template cross sections; bottom-quark; b -tagging

“I mean all the things that we really venerate and honor in our country and are patriotic about. It has nothing to do directly with defending our country except to help make it worth defending.”

– Robert R. Wilson, answering Congress’ question on how the new accelerator will affect the nation’s security.

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Chapter 1

Introduction

The Higgs boson [1, 2, 3, 4] is the only elementary scalar particle of the Standard Model (SM) [5, 6, 7, 8, 9] of particle physics and their interactions. It arises as a consequence of spontaneous electroweak symmetry breaking, due to the non trivial structure of a scalar field potential – the Higgs potential. Such scalar field permeates the universe and its interactions with the elementary particles originates their masses. In the past decades, many experimental tests – including the discovery of the W and Z bosons and of the heaviest quarks – have confirmed the predictions of the SM, which dates back from the sixties of the last century. However, the Higgs boson, while being sought for a long time, has escaped detection until very recently.

Only in July 2012, six years ago, the Higgs boson was finally discovered. The discovery took place at the Large Hadron Collider (LHC) at CERN, a proton-proton (pp) accelerator and collider in which protons collide at energies never produced by previous accelerators and at the highest instantaneous luminosity achieved so far in hadron colliders. The Higgs boson was discovered through the analysis of the proton-proton collisions collected at center-of mass energies of 7 and 8 TeV in the LHC Run 1 up to June 2012 by the two LHC multi-purpose experiments, ATLAS [10] and CMS [11]. These experiments are devoted to both the precise test of SM predictions (in electroweak, top quark and bottom quark physics) and to the search for signatures of physics processes beyond the Standard Model (BSM).

Since the Higgs boson is an unstable particle that decays very quickly, before interacting with the detector material, the Higgs boson was observed by reconstructing and identifying the products of its disintegrations in the decay modes with the cleanest signatures, for the most abundant of its production modes, which are gluon or vector boson fusion: the disintegrations to pairs of photons or of electroweak vector gauge bosons [12, 13]. The particle that was observed decaying to such final states had a mass around 125 GeV and decay rates consistent with the SM predictions for a Higgs boson with that mass.

After the discovery, the properties of the discovered particle have been measured using the full LHC Run 1 dataset, and were found to be in agreement with those predicted by the SM within uncertainties, typically of the order of $\pm 20\%$ [14, 15, 16, 17].

The observation of the Higgs boson decays to electroweak vector bosons permits measurements of the couplings between the Higgs boson and such bosons, showing good agreement with the SM prediction, in which such interactions – as well as the W and Z mass terms – arise from the kinetic term of the Higgs part of the lagrangian after spontaneous symmetry breaking. However, fermion masses and interactions between fermions and the Higgs boson originate from a separate term of the SM lagrangian, the one describing the Yukawa interactions between the fermion fields and the Higgs field. Observing Higgs boson decays to fermions and determining

the couplings between the Higgs boson and the fermions, is thus crucial to further probe the properties of the Higgs sector.

The $H \rightarrow b\bar{b}$ decay, which in the Standard Model is expected to have the largest branching ratio – of around 58% when Higgs mass is 125 GeV, allows a direct measurement of the Higgs boson coupling to bottom quarks. In addition, since in the SM the Higgs boson width is dominated by the partial width of $H \rightarrow b\bar{b}$, measuring the rate of such decay is important in order to extract information about the width of such particle, which is not measurable in a model-independent way at the LHC.

Observation of the $H \rightarrow b\bar{b}$ decay at a hadronic collider, however, is complicated, as demonstrated by the many years of searches performed at the Tevatron collider that only with the full data and the combination of the data of both Tevatron experiments, D0 and CDF, lead to a marginal evidence of such decay. Indeed, in July 2012, D0 and CDF [18] published the first evidence of $H \rightarrow b\bar{b}$ decays, based on the analysis of the data collected in the full Run 2 Tevatron data taking. A maximum local significance of 3.3 standard deviations for a Higgs boson mass of 135 GeV was obtained, corresponding to a global significance of 3.1 standard deviations.

The difficulty in isolating the Higgs boson decays to $b\bar{b}$ in hadron collisions stems from the fact that the main production modes of a Higgs boson with mass of 125 GeV, gluon-gluon fusion and vector boson fusion, which together correspond to about 94% of the total production cross section at the LHC, would produce – when followed by a $H \rightarrow b\bar{b}$ decay – a fully hadronic final state which is “drowned” in an overwhelmingly larger background from multi-jet QCD processes. To isolate $H \rightarrow b\bar{b}$ decays with reasonable signal-to-background ratio one has thus to look for production modes with much smaller cross sections but signatures – such as leptons with high transverse momentum – that are easier to identify and discriminate from QCD background. Such is the case of the production of a Higgs boson in association with a W or Z boson, when the boson decays to leptons.

With the full LHC Run 1 data, ATLAS and CMS, using about 25 fb^{-1} of pp collisions, reported mild excesses of events with respect to the SM (without Higgs boson) in the search for VH ($V = W, Z$), $H \rightarrow b\bar{b}$ production, with local significances of about 1.4 and 2.1 standard deviations [19, 20], respectively, yielding a combined observed significance of about 2.6 standard deviations. Searches were also performed in the VBF and $t\bar{t}H$ production modes, but with smaller sensitivities.

Providing a definite and solid answer about the nature of Higgs coupling to bottom-quarks is one of the main goals of the LHC Run 2. In this thesis I describe the search for the $VH(b\bar{b})$ process with the 13 TeV pp collisions collected by the ATLAS detector during the first three years (2015–2017) of the LHC Run 2, which has lead to the observation of $H \rightarrow b\bar{b}$. The same dataset has been used to perform a measurement of the VH production cross section with finer granularity, in exclusive fiducial regions of the phase space of Higgs boson production. This is also illustrated in this manuscript. I also provide some perspectives for these measurements with the 3000 fb^{-1} of 14 TeV pp collisions expected to be collected at the high-luminosity LHC by an upgraded ATLAS detector in the years 2026–2035.

Experimentally, one of the crucial ingredients of the $VH, H \rightarrow b\bar{b}$ search is the identification of b -jets (jets containing b -hadrons), in order to reject the large background from vector boson production in association with jets from light-flavoured quarks. A b -jet “tagging” algorithm has been developed in ATLAS [21], to identify b -jets with high efficiency and suppress jets from charm and light-flavour quark with large rejection factors. To properly measure the $VH, H \rightarrow b\bar{b}$ cross-section and the $H \rightarrow b\bar{b}$ branching ratio with high precision, a measurement of the b -tagging identification efficiency of b -jet is mandatory. The b -tagging efficiency calibration of b -jets is the other topic to which I have devoted the research activity of my Ph.D. thesis.

Structure of the thesis and personal contributions

The thesis consists of eight chapters. After this short introduction, Chapter 2 gives an overview of the Standard Model and in particular of the Higgs boson sector, from both the theoretical and experimental viewpoints. Despite all its successes in describing the observed phenomena, the Standard Model has also some limitations, that call for a more fundamental theory, as briefly discussed in the last section of that Chapter.

Chapter 3 describes the LHC accelerator complex, its design and actual performance, and the ATLAS detector, with its main sub-systems. A short outline of the data taking performance, together with the ATLAS trigger system, is provided at the end of this chapter.

The reconstruction in ATLAS of “high-level” objects, such as particle trajectories and momenta, as well as particle identification, from “low-level” electrical signals, and the performance of those algorithms, are reported in Chapter 4.

Given the relevance of b -jet identification in the context of this thesis, the algorithms used in ATLAS to identify b -jets and their performance are described separately, in Chapter 5. Also described in detail is how the b -jet efficiency of the tagging algorithm has been determined from a $t\bar{t}$ data control sample using a *tag-and-probe* technique. In this method, a sample of “probe” jets enriched in b -jets from $t\bar{t} \rightarrow WbWb \rightarrow e\nu\mu\nu b\bar{b}$ events is obtained by isolating a final state with an electron, a muon, large transverse momentum imbalance from the undetected neutrinos, and two jets of which one is identified as a b -jet and is referred to as the “tag”, while the other is not subject to any requirement. This method is different from the *PDF* method, based on a combinatorial likelihood approach, used in ATLAS in Run 1 for the b -tagging efficiency calibration. I have worked on that since I joined the ATLAS collaboration in 2015, developing the technique and implementing it in the ATLAS software framework. I have optimised the selection, including a multivariate discriminant to further enhance the b -jet purity of the selected probe jet sample, and performed the calibration, which includes also a full identification of all the sources of systematic uncertainties and the estimation of their impact on the measurement. The results of my work, performed on the ATLAS data collected in 2015 and 2016, have been described in a recent publication [22]. They are in good agreement, with similar or smaller uncertainties, with those of the *PDF* method – applied to the same data – used already in Run 1. From these measurements, data-over-simulation efficiency scale factors were determined and propagated to all simulated samples of processes with b -jets used by ATLAS analyses, including the search of VH , $H \rightarrow b\bar{b}$ decays with the same (*i.e.* 2015–2016) dataset. More recently, I have worked on the calibration of the b -jet tagging efficiency of the algorithm that has been retuned for the analysis of the ATLAS data collected between 2015 and 2017, which has been reconstructed with a newer release of the ATLAS software that uses new algorithms. The final calibration is in progress, including in particular further studies on the optimisation of the selection to further reduce the uncertainty on the measured efficiency; a preliminary version was used, together with the results of the *PDF* method on the same data, for the VH , $H \rightarrow b\bar{b}$ search based on the 2015–2017 data.

The search for the associated production of a Higgs boson with a vector boson, VH , followed by a decay of the Higgs boson to a b -quark pair, $H \rightarrow b\bar{b}$, with the 13 TeV pp collisions collected by ATLAS in Run 2 is described in Chapters 6 and 7. Two analyses are described. The first one, extensively described in Chapter 6, is based on 36 fb^{-1} of data collected in 2015 and 2016, and was published in Ref. [23]. Such analysis led to a large evidence for VH , $H \rightarrow b\bar{b}$, with an observed significance of 3.5 standard deviations. A second analysis, very similar to the previous one but with the addition of 44 fb^{-1} of data collected in 2017, was recently published in Ref. [24]. Such analysis led to an evidence for VH , $H \rightarrow b\bar{b}$ close to the conventional “ 5σ ” threshold for claiming a discovery, with an observed significance of 4.9 standard deviations; in combination

with other $H \rightarrow b\bar{b}$ ATLAS searches, it led to an observation of this decay. In Chapter 7 only the differences of this analysis with respect to the previous analysis and the updated results are highlighted. The results of a similar search by the CMS experiment [25] are also detailed. During my Ph.D. thesis, and in the year before it started, as a master student, I have been working on the VH , $H \rightarrow b\bar{b}$ search with ATLAS Run 2 data since its beginning. For the analysis of the 2015 and 2016 data I contributed to the development and validation with early Run 2 data – particularly on the “0-lepton” channel of the analysis framework, and was one of the main developers of the full statistical analysis of the selected sample, including the implementation of the final fit to the various signal and control regions of the analysis, the fit to the diboson control sample to determine the diboson signal strength and calibrate the analysis with a SM “candle” such as the VZ , $Z \rightarrow b\bar{b}$ process, and all the studies of the fit pulls and covariance matrices to understand the solidity of the results, in both the fit of the nominal analysis and of that of the so-called “dijet-mass” analysis, used to cross-check the nominal one with a fit to a simpler and more intuitive discriminant variable (the two b -jet invariant mass instead of a multivariate discriminant combining together information from several correlated quantities). I also gave an important contribution by calibrating the b -tagging b -jet efficiency, whose uncertainty in Run 2 is quite reduced compared to Run 1. For the analysis including data collected in 2017, I was mainly involved in further development and validation of the analysis framework (based on a new ATLAS software release) with data/simulation early comparisons based on 2017 data and helped younger fellow students in ATLAS to perform the statistical interpretation of the selected data sample. I also performed a preliminary calibration of the b -tagging algorithm redefined for the analysis of 2015–2017 data in the new ATLAS software released, as mentioned before when discussing the content of Chapter 5.

Chapter 7 also discusses two further studies that followed the observation of the $H \rightarrow b\bar{b}$ decay. The first study is the measurement of simplified template cross section (STXS) for the VH production mode using $H \rightarrow b\bar{b}$ decays. Simplified template cross sections are measurements of the VH cross section in a simplified fiducial volume with a finer granularity than the inclusive measurement presented in the previous chapter. They are defined based on production properties such as the V boson transverse momentum or the number of jets produced in association with the Higgs boson and the vector boson. The more detailed information provided by this extra granularity makes the measurements more useful to test SM predictions and more sensitive to BSM effects, which might “hide” themselves in scarcely populated high-vector-boson transverse momentum bins. The use of fiducial volumes also make the measurements less sensitive to theory prediction uncertainties, unlike the case of the “signal strength”, *i.e.* the ratio between the total observed and expected VH , $H \rightarrow b\bar{b}$ cross sections, measured in Ref. [24]. I was one of the leading contributors to this measurement. First, I made the STXS information (fiducial region, truth-level vector boson transverse momentum and number of jets) available in the simulated signal samples produced centrally by ATLAS and used for this analysis. Then, I extended the analysis framework of the VH , $H \rightarrow b\bar{b}$ analysis to retrieve such information, and used it to compute the expected number of events, acceptance, expected distribution of the discriminant variable used in the final fit, for each STXS region. I also discussed and worked with ATLAS colleagues and with theorists of the LHC Higgs cross section working group to properly estimate the residual impact of the QCD scale and PDF+ α_s theoretical uncertainties on the STXS measurement. Finally I extended the VH , $H \rightarrow b\bar{b}$ statistical analysis code to incorporate such additional uncertainties and to accommodate a fit with the cross sections in the STXS regions as multiple parameters of interest.

The second study described in Chapter 7 is a perspective study of the VH , $H \rightarrow b\bar{b}$ analysis with 3000 fb^{-1} of 14 TeV pp collisions expected to be collected at the high-luminosity LHC

by an upgraded ATLAS detector in the years 2026–2035. The work builds upon the results of Ref. [24], which are extrapolated to the high-luminosity regime by taking into account the larger integrated luminosity, the higher cross sections for both signal and background production, the expected improvements in detector performance and the foreseen progresses in the theoretical modelling of the signal and of the background processes. I have performed the study, based on assumptions on the theoretical and experimental performance centrally provided by the ATLAS Collaboration, in the broader context of the “Yellow report” under preparation for the 2019 update of the European particle physics strategy.

Finally, Chapter 8 summarises the work presented in the thesis, with some personal remarks on its limitations and its future perspectives.

Chapter 2

Theoretical and Experimental Overview of the Higgs Boson

2.1 The Standard Model of Particle Physics

2.1.1 The Standard Model particles and interactions

The Standard Model (SM) of elementary particles and of their fundamental interactions [5, 6, 7, 8, 9] is a quantum field theory, formulated in the sixties and the seventies of the twentieth century, that describes with excellent accuracy three (strong, weak, and electromagnetic) of the four, known interactions between the known particles. Only the gravitational force, described instead by Einstein’s general relativity and for which a complete and consistent quantum-mechanical formulation is not available, is not described by the Standard Model. Until today, all phenomena involving the known particles (except gravitational ones) are perfectly described by the Standard Model; however, as it will be mentioned later, some observations call for an extension of the SM to a more complete theory, of which the Standard Model would only be a low-energy approximation.

In the Standard Model, the elementary constituents of matter are fermions of spin $1/2$. They are organised in multiplets, according to the way their wave function behaves under local gauge transformations. The fundamental interactions between such particles are mediated by bosonic fields of spin 1. Such fields arise naturally, in the mathematical formulation of the theory, when requiring that the lagrangian is invariant under some local gauge group: for each generator of the group there is a corresponding massless vector boson that appears into the theory and that couples to fields whose wave functions do not transform trivially under the gauge group. The elementary particles and fundamental force fields described by the Standard Model are illustrated in Figures 2.1 and 2.2, respectively.

The observed pattern of charges and interactions can be reproduced by postulating that the Standard Model lagrangian is invariant under the local gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, where the $SU(3)_C$ group corresponds to the strong interactions, with 8 massless generators (the gluons), while $SU(2)_L$ and $U(1)_Y$ are the weak isospin and the weak hypercharge, corresponding (after the process of “spontaneous electroweak symmetry breaking” described later) to the weak and electromagnetic forces.

All observed particles can be described in terms of elementary quarks and leptons. Quarks exist in six flavours, up (u), down (d), charm (c), strange (s), top (t), bottom (b), with fractional charge Q ($+2/3$ for up, charm and top, and $-1/3$ for the others, in units of the positron charge), together with their antiparticles. Quarks carry a “color charge”, which comes in three flavours,

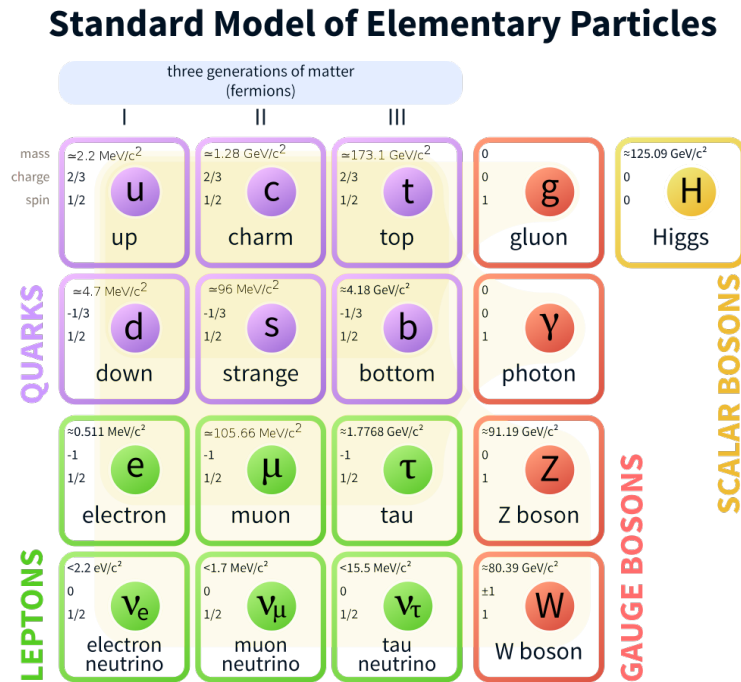


Figure 2.1 – The Standard Model of elementary particles, with the three generations of matter, gauge bosons in the fourth column, and the Higgs boson in the fifth (source: wikipedia).

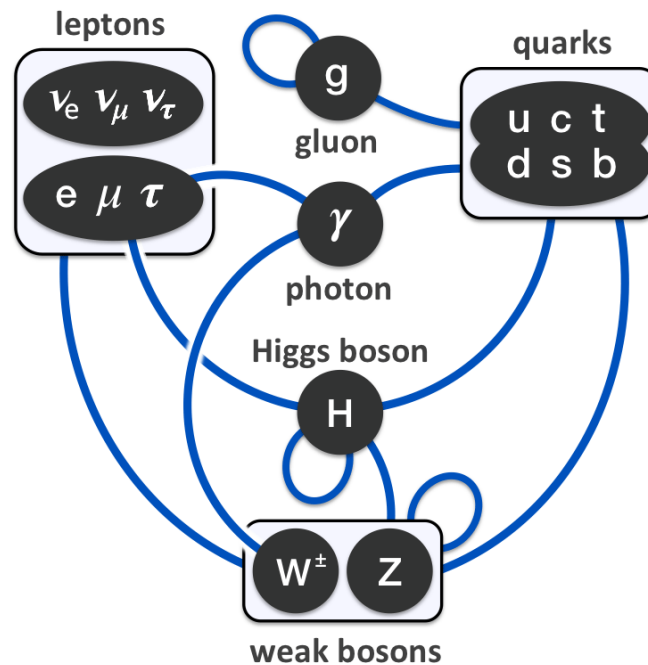


Figure 2.2 – The fundamental interactions between elementary particles described by the Standard Model (source: wikipedia).

red (r), green (g) and blue (b); the quark fields belong to $SU(3)_C$ triplets and as a consequence quarks interact with each other by means of gluon exchange. Due to the non-abelian structure of the $SU(3)_C$ group, gluons themselves are colored and can interact with each other. The theory describing the strong interactions between quarks is called Quantum Chromodynamics (QCD).

Leptons do not carry a color charge, their wave functions are color singlet and thus they are not subject to strong interactions. Hadrons (particles like the proton, the neutron or the pions) are strongly interacting particles (of which there are several hundreds!) which nowadays are explained as bound states of quarks, kept together mainly by strong interactions among the constituent quarks. The strong interactions among hadrons are the “remnant” of the interactions between their quarks. Hadrons could be classified as: baryons, made of three quarks (or three antiquarks), with half-integral spin (thus fermions), and mesons, made of quark-antiquark pairs, with integral spin (thus bosons) and other category.

According to the principles of QCD, and in particular to “color confinement”, bound states of quarks are color-neutral. The most probable combinations that satisfy this constraint are indeed the three-quark and quark-antiquark combinations. Two-quark pairs are forbidden, but more exotic states (like “tetraquark” states, formed by two quark and two antiquarks, or “pentaquark” states, formed by three quarks plus a quark-antiquark pair) are allowed and recently a few of them started to be observed. Color confinement means that separating quarks to an infinite distance requires an infinite amount of energy, and, as a consequence, free quarks cannot exist. When a quark is pulled away from a hadron in a hard scattering process, the potential energy increase due to the separation between these quarks and its former partners leads to the creation of new quark-antiquark pairs and gluons (“fragmentation”), and the process can lead to a cascade of similar events that end up when the quarks and gluons rapidly form new bound states. This process is called “hadronisation”.

With respect to weak and electromagnetic interactions, or to the $SU(2)_L \otimes U(1)_Y$ part of the gauge symmetry group of the SM lagrangian, both leptons and quarks are arranged - according to their chirality - in left-handed doublets and right-handed singlets. The doublets are formed by particles with the same value of the weak hypercharge Y but different values of the third component T_3 of the weak isospin ($\pm 1/2$), and their charges differ by one unit: two such doublets are formed by the up (u) and down (d) quarks, and by the electron-neutrino (ν_e) and the electron (e). The six quarks and the six leptons (e , μ , τ and corresponding neutrinos) form three families (or generations) which replicate the same gauge structure but differ in the masses of the particles. To summarise, with respect to $SU(3)_C \otimes SU(2)_L$, the quarks and leptons form three families whose wave functions transform according to the representations 3×2 , 3×1 (left-handed or right-handed quarks) and 1×2 , 1×1 (left-handed or right-handed leptons). Neutrinos are massless and purely left-handed.

Mixing among different families, or couplings between different flavours, is induced in the quark sector by the Cabibbo-Kobayashi-Maskawa (CKM) matrix and in the neutrino sector by the Pontecorvo-Maki-Nakagawa-Sakato (PMNS) matrix. Irreducible complex phases in these two matrices induce violation of the CP symmetry, one of the necessary conditions to explain the matter-antimatter asymmetry of the universe.

2.1.2 The Standard Model lagrangian

The Standard Model lagrangian can be derived as a lagrangian that satisfies the Lorentz invariance, the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ local gauge invariance, and that is renormalisable.

The QCD part of the lagrangian is given by

$$\mathcal{L}_{\text{QCD}} = \sum_{\psi} \bar{\psi}_i \left(i\gamma^\mu (\partial_\mu \delta_{ij} - ig_s G_\mu^a T_{ij}^a) - m_\psi \delta_{ij} \right) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}, \quad (2.1)$$

where ψ are the Dirac spinors of the quark fields, $i = r, g, b$ is the color index, G_μ^a ($a = 1..8$) are the 8 gluon fields, T_{ij}^a are the generators of $SU(3)$ (the Gell-Mann matrices), $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c$ are the gluon field strength tensors (f^{abc} are the $SU(3)$ structure constants), and g_s is the strong coupling constant.

The electroweak (EW) part of the lagrangian is

$$\mathcal{L}_{\text{EW}} = \sum_{\psi} \bar{\psi} \gamma^\mu \left(i\partial_\mu - g' \frac{1}{2} Y B_\mu - g \frac{1}{2} \tau_L^a W_\mu^a \right) \psi - \frac{1}{4} W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \quad (2.2)$$

where Y is the weak hypercharge ($U(1)_Y$ generator), τ_L^a ($a = 1..3$) are the three $SU(2)_L$ generators (Pauli matrices, acting only on left-handed chiral fermions), B_μ and W_μ^a are the $U(1)_Y$ and $SU(2)_L$ gauge fields, $B_{\mu\nu}$ and $W_{\mu\nu}^a$ are the corresponding field strength tensors, and g' and g are their coupling constants.

2.1.3 The Higgs mechanism

The problem with the lagrangian written so far is that fermion mass terms of the form $m\bar{\psi}\psi$ are not invariant under $SU(2) \otimes U(1)$, nor are the boson mass terms. As a consequence, all elementary particles and force carriers are expected to be massless. Moreover, it is not possible to identify the interactions described by the electroweak lagrangian with the familiar electromagnetic and weak forces, as the $U(1)$ hypercharge field couples for instance also to neutrinos, unlike the electromagnetic force which only couples to charged particles.

The common solution to these two apparently unrelated problems was found in 1964 through the so-called BEH mechanism of spontaneous electroweak symmetry breaking [1, 2, 4, 3]. The solution consists in introducing an additional doublet (under $SU(2)_L$) of complex scalar fields, the Higgs field, with weak hypercharge equal to 1:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \quad (2.3)$$

In addition to the kinetic term and the couplings to the $SU(2)$ and $U(1)$ bosons, the Higgs field also has a potential $V(\phi)$ with a “mexican-hat” shape. The Higgs lagrangian is:

$$\mathcal{L}_H = \phi^\dagger \left(\partial_\mu - \frac{i}{2} (g' Y B_\mu + g \tau_L^a W_\mu^a) \right) \left(\partial^\mu + \frac{i}{2} (g' Y B^\mu + g \tau_L^a W^{\mu a}) \right) \phi - V(\phi), \quad (2.4)$$

with the potential V having the form:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (2.5)$$

The introduction of the Higgs field makes it possible to add to the lagrangian extra terms that are gauge invariant and renormalisable, representing the “Yukawa” interactions between the Higgs field and the fermions:

$$\mathcal{L}_{\text{Yukawa}} = y_{\alpha\beta}^l \bar{L}_\alpha l_\beta H + y_{\alpha\beta}^d \bar{Q}_\alpha D_\beta H + y_{\alpha\beta}^u \bar{Q}_\alpha U_\beta \tilde{H} + \text{hermitian conjugate} \quad (2.6)$$

Here $y_{\alpha\beta}$ are 3×3 Yukawa matrices of couplings between generations α and β , and $\tilde{H} = i\tau_2 H^\dagger$.

For $\mu^2 < 0$, the Higgs boson potential has an infinite set of equivalent (under the gauge group symmetry) minima, corresponding to the solution

$$|\phi|^2 = \frac{-\mu^2}{2\lambda} \quad (2.7)$$

Spontaneous symmetry breaking occurs because the minimum of the potential realised in nature is one of such solutions, breaking the initial symmetry of the system. The mathematical equations of the system then need to be expanded around such minimum, to find the actual behaviour of the particles and the fields. Choosing the most convenient basis (“unitarity gauge”), one can assume that the minimum of the Higgs potential is of the form

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (2.8)$$

where

$$v = \sqrt{\frac{-\mu^2}{\lambda}} \quad (2.9)$$

is the “vacuum expectation value” (vev) of the Higgs field, and that the Higgs field itself is given by

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}. \quad (2.10)$$

where v is thus a real constant and $H(x)$ a real scalar field, which in the following will be called the Higgs boson field.

The expansion of the previous equations around the minimum (Eq. 2.8) leads to several important consequences:

- first, the bosonic part of the electroweak and the Higgs lagrangians become:

$$\begin{aligned} & \frac{1}{2} \partial_\mu H \partial^\mu H + \mu^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 \\ & + \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z^\mu \\ & + \frac{g^2 v}{2} W_\mu^+ W^{-\mu} H + \frac{1}{2} \frac{(g^2 + g'^2) v}{2} Z_\mu Z^\mu H \\ & + \frac{g^2}{4} W_\mu^+ W^{-\mu} H^2 + \frac{1}{2} \frac{g^2 + g'^2}{4} Z_\mu Z^\mu H^2. \end{aligned} \quad (2.11)$$

The first line describes the kinetic term, the mass term, and the trilinear and quartic self couplings of the Higgs boson scalar field. The mass is given by

$$m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}, \quad (2.12)$$

the trilinear self-coupling is

$$\lambda_{3H} = \lambda v = \frac{m_H^2}{2v}, \quad (2.13)$$

and the quartic self-coupling is

$$\lambda_{4H} = \frac{\lambda}{4} = \frac{m_H^2}{8v^2}. \quad (2.14)$$

The second line introduces mass terms for the $W^\pm$ and Z bosons, and the last two lines describe the coupling between the Higgs boson field and the $W^\pm$ and Z bosons. The kinetic and tensor terms of the spin-1 fields have been omitted. The W^+ and W^- bosons here are linear combinations of the first two components of the W field,

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (2.15)$$

The Z boson appears, together with another spin-1 field A_μ which can be identified with the photon as shown later (by looking at the interaction part of the electroweak lagrangian), as a linear combination of the W^3 and B fields:

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \quad (2.16)$$

The ‘‘Weinberg angle’’ θ_W is given by

$$\cos^2\theta_W = \frac{g^2}{g^2 + g'^2} \quad (2.17)$$

According to the second line of Eq. 2.11, the masses of the W and Z bosons are given by:

$$m_W = \frac{gv}{2} \quad (2.18)$$

$$m_Z = \frac{\sqrt{g^2 + g'^2}v}{2} = \frac{m_W}{\cos\theta_W} \quad (2.19)$$

while no mass term arises for the photon field A . From the measured values of the W and Z boson masses one can infer the value of the Weinberg angle, $\sin^2\theta_W = 0.222$. The third line implies that the couplings between the Higgs boson and the W and Z bosons (also denoted V bosons in the following) are proportional to their masses squared, being equal to

$$g_{HVV} = \frac{m_V^2}{v}. \quad (2.20)$$

- second, the Yukawa lagrangian containing the interactions between the Higgs field and the fermions becomes, together with the free fermion kinetic terms of the QCD and EW lagrangians:

$$\sum_i \bar{\psi}_i \left(i\gamma^\mu \partial_\mu - m_i - \frac{m_i H}{v} \right) \psi_i, \quad (2.21)$$

where one can recognise the kinetic and mass terms of the fermions, as well as the couplings between the fermions and the Higgs boson field such Yukawa couplings are flavor diagonal and are proportional to the fermion masses, being equal to

$$g_{Hff} = \frac{m_f}{v} = \frac{gm_f}{2m_W}. \quad (2.22)$$

- third, the interaction part of the electroweak lagrangian, expressed in terms of the physical bosons $W^\pm$, Z , A , becomes:

$$\begin{aligned}
 & - e \sum_{\psi_i} Q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \\
 & - \frac{g}{2\sqrt{2}} \sum_{\psi_i} \bar{\psi}_i \gamma^\mu (1 - \gamma^5) (\tau^+ W_\mu^+ + \tau^- W_\mu^-) \psi_i \\
 & - \frac{g}{2\cos\theta_W} \sum_{\psi_i} \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu.
 \end{aligned} \tag{2.23}$$

In the first line, $e = g \sin\theta_W$ and Q_i is equal to $T_3 + \frac{Y}{2}$, which leads to the Dirac interaction lagrangian between the photon field A_μ and the elementary fermions if e is identified with the positron charge and with the proper assignment of the hypercharge to the fermions ($Y = 1/3$ for left-handed quarks, $4/3$ and $-2/3$ for right-handed up-type or down-type quarks, -1 for left-handed leptons, and -2 for right-handed charged leptons).

The second line, where $\tau^\pm$ are defined as $\frac{1}{2}(\tau^1 \pm i\tau^2)$, describe the charged-current weak interactions, with the typical $V - A$ structure given by the $\gamma^\mu(1 - \gamma^5)$ term, which implies that the W boson only couples to left-handed quarks and leptons. For leptons, the charged-current interaction is flavour-diagonal, as written in the previous expression; for quarks, the interaction actually “mixes” quarks of different flavours, with mixings given by the elements of the CKM matrix. This is a consequence of the fact that the quark mass eigenstates and the weak interaction eigentstates are not the same. When expressing the weak mass eigenstates in terms of the quark mass eigenstates, such non-diagonal interactions arise, and the quark interaction lagrangian actually becomes:

$$-\frac{g}{2\sqrt{2}} \sum_{i,j} \left(\bar{u}_i \gamma^\mu (1 - \gamma^5) V_{ij}^{\text{CKM}} d_j \right) W_\mu^+ + \text{hermitian conjugate}, \tag{2.24}$$

where V_{ij}^{CKM} is the CKM matrix, a 3×3 unitary matrix. The charged-current weak interaction is responsible for instance for the muon decay; measurements of the muon lifetime can be directly translated into determinations of the Higgs field vev, leading to a value of v around 246 GeV.

The third line corresponds to the neutral-current weak interactions, and the vector and axial-vector couplings are given by $g_V^i = T_3^i - 2Q_i \sin^2\theta_W$, $g_A^i = T_3^i$.

2.2 Higgs Boson Phenomenology at the LHC

The Higgs boson is the scalar particle associated to the Higgs boson field. In the Standard Model, the Higgs boson is predicted to be a neutral, CP -even scalar ($J^{PC} = 0^{++}$). Its mass, m_H , and thus also the self-coupling λ , is a free parameter of the theory. However, when the mass of the Higgs boson is fixed, given that its couplings are all known, the production rates and the partial widths of the Higgs boson can be calculated.

2.2.1 Higgs boson production

At the LHC, the Higgs boson is produced as a consequence of the hard scattering between quarks and gluons inside the colliding protons. The quarks and gluons carry a fraction x of the momentum of the incoming protons; the probability distributions of the momentum fraction x are called the proton parton distribution functions (PDF) and are determined from global fits to several observables measured in collider experiments. Such distributions for two values of the momentum transfer, as obtained from the global fit performed by the NNPDF Collaboration, are illustrated in Fig. 2.3. The $pp \rightarrow H + X$ cross section is thus the convolution over x of the elementary $qq \rightarrow H$ or $gg \rightarrow X$ cross sections and the quark and gluon distribution functions.

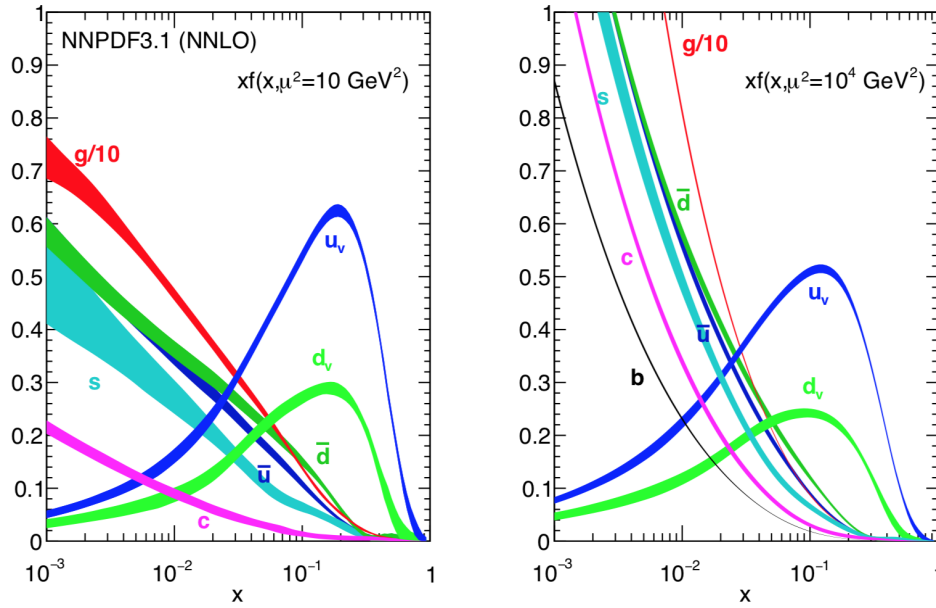


Figure 2.3 – The NNPDF3.1 NNLO proton PDFs, evaluated at $\mu^2 = 10 \text{ GeV}^2$ (left) and $\mu^2 = 10^4 \text{ GeV}^2$ (right).

Different qq and gg scattering processes can lead to the production of the Higgs boson. Since the coupling of the Higgs bosons to the gluons is null and the couplings of the Higgs boson to the most abundant quarks in the proton, the light ones, are vanishingly small, the Higgs boson is not produced directly in a ggH or qqH vertex, but passes through the production of intermediate heavier vector bosons or quarks.

The main Higgs boson production modes at the LHC are illustrated in Fig. 2.4, and their predicted cross sections as a function of the Higgs boson mass for a pp center-of-mass energy of 13 TeV are shown in Fig. 2.5. All figures and numbers relating to the theoretical Higgs production cross sections and branching ratios in this document are taken from the LHC Higgs cross section working group [26, 27, 28, 29], which compiles regularly the most-updated list of predictions. The process with the largest cross section, except at very high values of the Higgs boson mass, is gluon-gluon fusion (ggF), mediated by a top-quark loop. The process with the second largest cross section, for m_H greater than about 100 GeV and which becomes the dominant one for m_H above approximately 1 TeV, is vector-boson fusion (VBF), *i.e.* the “fusion” into a Higgs boson of two vector bosons emitted by two colliding quarks, which are then scattered close to the initial proton direction, leading to a typical signature of a Higgs boson in the central part of the

detector and two “jets” of hadrons from the quarks in the forward region, with large separation in polar angle. Processes with smaller cross sections are the associated production with a W or Z boson (VH , $V = W, Z$), also called Higgsstrahlung, in which a quark and an antiquark give rise to a vector boson which then radiates a Higgs boson, and the associated production with a $t\bar{t}$ pair ($t\bar{t}H$), in which two colliding gluons emit $t\bar{t}$ pairs and one top from one gluon and an anti-top from the other combine into a Higgs boson. ZH also has a contribution from the two-gluon initial final state, through a quark loop-mediated Feynman diagram. In the associated production modes, the signature of the signal is quite clean, with either a heavy vector boson decaying either to a lepton or quark pair, or with a pair of heavy top quarks that decay to two bottom quarks and two W bosons, with the W bosons further decaying to lepton or quark pairs. On the other hand the associated production with a $b\bar{b}$ pair, $b\bar{b}H$, has similar cross section to $t\bar{t}H$ but it is hardly distinguishable from ggF plus jet emission, which is about two order of magnitudes more probable.

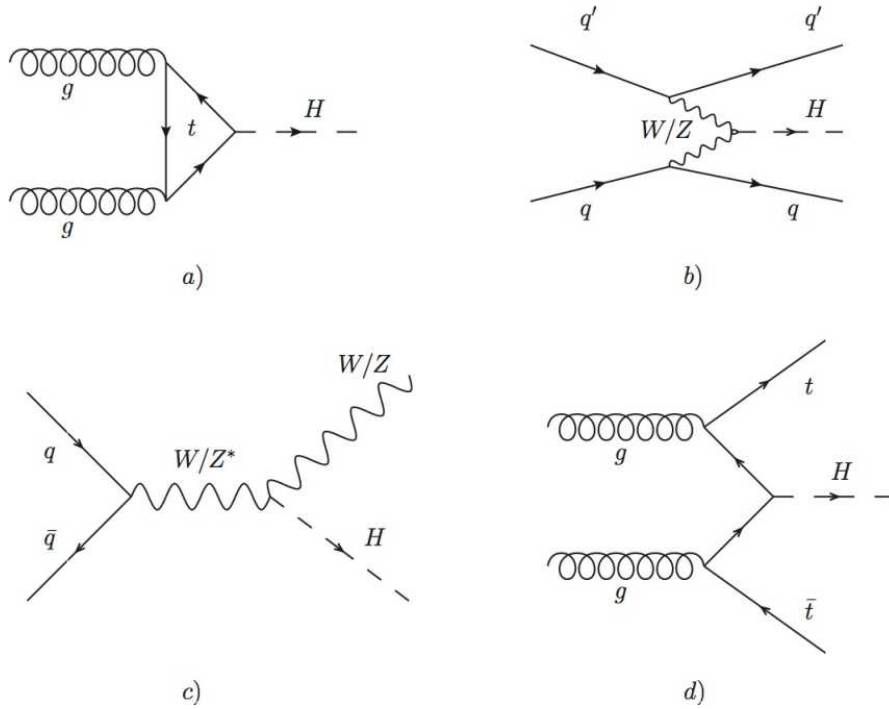


Figure 2.4 – Some of the Feynman diagrams for the main Higgs boson production modes in pp collisions at the LHC: (a) gluon-gluon fusion, (b) vector-boson fusion, (c) associated production with a vector boson, (d) associated production with $t\bar{t}$.

The production cross sections decrease with the Higgs boson mass, as shown in Fig. 2.5, but increase with the pp center-of-mass energy, as shown in Fig. 2.6, since the fraction of quarks and gluons with sufficient momentum inside the proton to produce the Higgs boson (plus the additional objects like a $t\bar{t}$ pair in $t\bar{t}H$ production) increases. For instance, between a pp center-of-mass energy of 7 TeV, as in the initial data-taking of the LHC in 2010 and 2011, and the current value of 13 TeV, the gluon-gluon fusion cross section approximately doubles, while the $t\bar{t}H$ cross section is around a factor four larger.

The production cross sections predicted by the SM for a 125 GeV Higgs bosons are listed in Table 2.1.

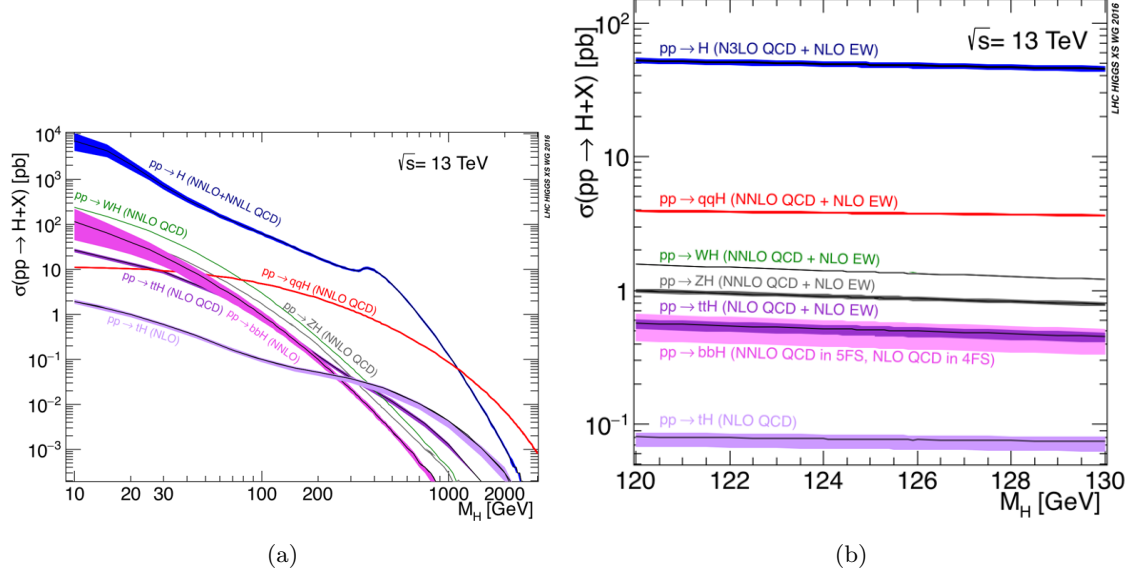


Figure 2.5 – Higgs boson production cross sections in 13 TeV pp collisions as predicted by the Standard Model, as a function of the Higgs boson mass, for (a) m_H between 10 GeV and 2 TeV, and (b) m_H between 120 and 130 GeV.

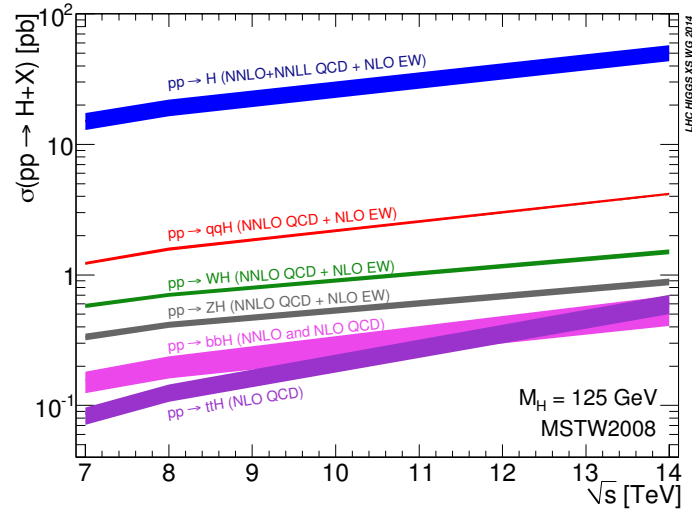


Figure 2.6 – Higgs boson production cross sections in pp collisions as predicted by the Standard Model, as a function of the pp center-of-mass energy, for a Higgs boson mass of 125 GeV.

Table 2.1 – Production cross sections for the main production modes of a Higgs boson with a mass of 125 GeV, for various pp center-of-mass energies.

Production mode	$\sigma_7 \text{ TeV [pb]}$	$\sigma_8 \text{ TeV [pb]}$	$\sigma_{13 \text{ TeV [pb]}}$
ggF ($pp \rightarrow H$)	16.85	21.42	48.58
VBF ($pp \rightarrow qqH$)	1.241	1.601	3.782
WH ($pp \rightarrow WH$)	0.577	0.703	1.373
ZH ($pp \rightarrow ZH$)	0.339	0.421	0.884
ttH ($pp \rightarrow ttH$)	0.089	0.133	0.507
bbH ($pp \rightarrow bbH$)	0.155	0.202	0.488
Total	19.25	24.28	55.61

2.2.2 Higgs boson decays

Once the mass of the Higgs boson is known, the partial widths for their decay to various final states can be computed, and thus the total width, which is simply the sum of the partial widths, and the branching ratio (BR) of a certain decay, which is the ratio between its partial width and the total width. The total width as a function of the Higgs boson mass, as predicted by the Standard Model, is shown in Fig. 2.7, while the branching ratios of various decays are shown in Fig. 2.8.

For Higgs boson masses below about twice the W boson mass, *i.e.* around 160 GeV, the decays to massive final state particles like W and Z bosons or top quarks are suppressed by the kinematic thresholds and since the bosons would be off-shell. The dominant decays are those to final state particles with small couplings to the Higgs boson, leading to a small total width, below 10 MeV, and the Higgs boson is thus a particle of rather narrow natural width (but its lifetime is anyway sufficiently short that it disintegrates immediately after production). For m_H above 160 GeV, the WW channel is fully “open”, and above 184 GeV (twice the Z boson mass) this is the case also for the ZZ channel. The width rapidly increases by two order of magnitudes, to 1 GeV, and then keeps increasing with the Higgs boson mass. For m_H around 600 GeV the total width is about 100 GeV, and the Higgs boson becomes a particle of rather broad natural width.

The favoured decay modes of the Higgs boson depend on its mass, given that – as said before – final states with heavy particles can be only produced abundantly if the Higgs boson mass is above the kinematic threshold for their production. As shown in Fig. 2.8, a heavy Higgs boson ($m_H > 160$ GeV) decays preferentially to WW and then to ZZ . Above the top kinematic threshold $2 m_t$ ($m_H > 350$ GeV) the Higgs to $t\bar{t}$ decays has also a large branching ratio. For a very light Higgs boson, with mass below approximately 100 GeV, the decays to WW and ZZ are heavily suppressed, and the Higgs boson decays to fermions lighter than the top, with branching ratios that scale with the square of the masses of the fermions: in decreasing order of BR, $b\bar{b}$, then $\tau\tau$, then $c\bar{c}$ and so on. The Higgs boson decays with quite large BR also to gluon pairs; as for ggF, the decay is mediated by top-quark loops, since the Hgg coupling is zero. Loop amplitudes, mediated by either W bosons or top quarks, also induced non-zero effective couplings to photons, leading to BR at the per mil level for the $H \rightarrow \gamma\gamma$ decay. For a light Higgs boson with mass in the range between around 100 and 160 GeV, both the fermionic final states (except $t\bar{t}$ due to the kinematic threshold and $q\bar{q}$, $q = u, d, s$ due to the very small couplings) and the bosonic ones are accessible, and the Higgs boson can thus be reconstructed in several different ways.

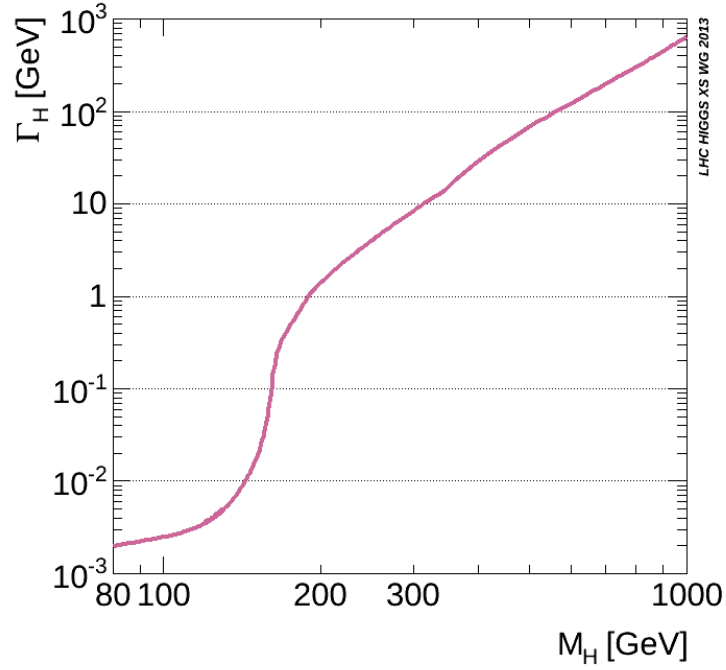


Figure 2.7 – Higgs boson width as predicted by the Standard Model, as a function of the Higgs boson mass, for m_H between 80 GeV and 1 TeV.

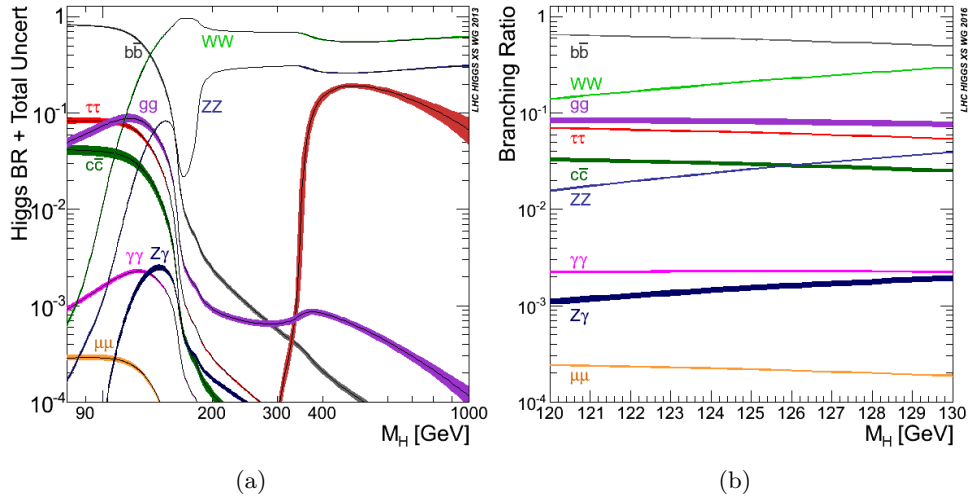


Figure 2.8 – Higgs boson branching ratios to various final states as predicted by the Standard Model, as a function of the Higgs boson mass, for (a) m_H between 80 GeV and 1 TeV, and (b) m_H between 120 and 130 GeV.

The decay branching ratios predicted by the SM for a 125 GeV Higgs boson are listed in Table 2.2.

Table 2.2 – Branching ratios of the decays to various final states of and total width of a Higgs boson with a mass of 125 GeV.

Decay mode	BR
$b\bar{b}$	58.24%
$c\bar{c}$	2.89%
$\tau^+\tau^-$	6.27%
$\mu^+\mu^-$	0.02%
gg	8.19%
$\gamma\gamma$	0.23%
$Z\gamma$	0.15%
WW	21.37%
ZZ	2.62%
Total Width	4.1 MeV

2.3 Higgs Boson Measurements at the LHC

2.3.1 Higgs boson discovery

In July 2012 the ATLAS and CMS Collaborations discovered a new particle, with a mass near 125 GeV, produced in the pp collisions of the LHC, and decaying to pairs of photons, Z bosons or W bosons [12, 13]. The analysis was based on about 5 fb^{-1} of data collected at a pp center-of-mass energy of 7 TeV and 5 fb^{-1} of data collected at 8 TeV, during the first data taking period of the LHC (Run 1).

The observation of the Higgs boson signal proceeds in the following way: an event selection is performed to identify candidate events with a final state consistent with the production of a signal under study; the backgrounds from Standard Model processes are studied and estimated, with the help of control samples in data and of simulations; the yield of events in data, in excess with respect to the estimated background, is considered as due to the signal. The significance of such a signal is estimated by computing the “ p -value”, *i.e.* the probability that a background fluctuation would lead to an excess as significant as the one observed in the data. The signal yield is then corrected for acceptance and efficiency effects, determined from simulated signal samples, and for the integrated luminosity of the selected data sample, to measure the product of the signal cross section times branching ratio to the final state under study and then compare it to the predictions from the theory. The p -value as a function of the Higgs boson mass of the “discovery” ATLAS and CMS publications are shown in Figure 2.9.

The estimation of the background and signal yields in the selected data sample is usually performed by means of a maximum likelihood fit to a discriminant variable, whose distribution differs between signal and background events. Typically such variable is the invariant mass of the decay products of the Higgs boson, such as the diphoton invariant mass in the case of the $H \rightarrow \gamma\gamma$ decay, since the distribution for such variable is smooth for background, non-resonant, events, while for the signal it is peaked around the true Higgs boson mass, with a width driven by the experimental photon energy resolution (since the intrinsic width of the Higgs boson for $m_H = 125 \text{ GeV}$ is negligible compared to the resolution). For more complex final states,

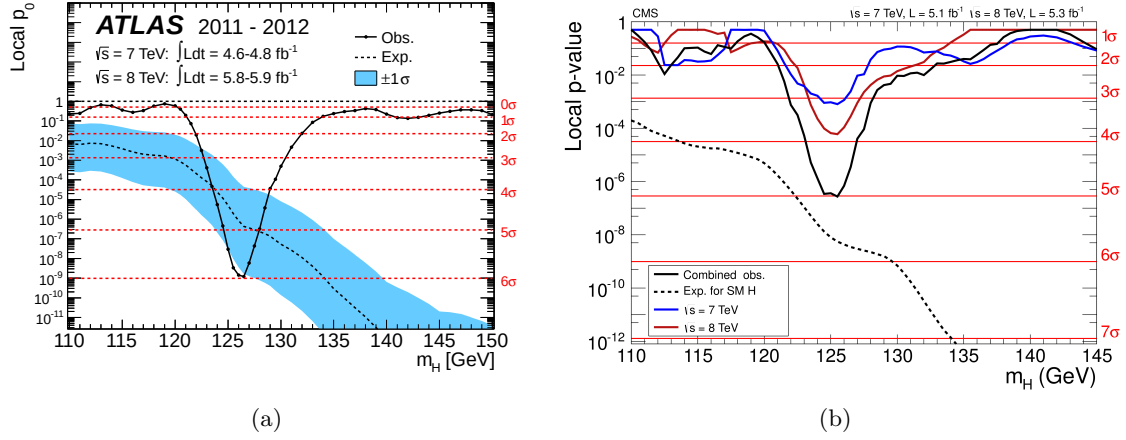


Figure 2.9 – The observed local p -value for 10 fb^{-1} of 7 TeV and 8 TeV data, from the combined analysis of Higgs boson decays to $\gamma\gamma$, ZZ and WW by (a) ATLAS and (b) CMS. The dashed line shows the expected local p -values for a SM Higgs boson with a mass m_H .

to increase the separation between signal and background, a multi-dimensional fit to several discriminating variables, or a one-dimensional fit to a multi-variate discriminant combining several separating variables into a single output, are performed.

As can be seen from Table 2.2, the bosonic final states WW , ZZ and $\gamma\gamma$ in which the Higgs boson has been discovered are not the ones with the largest branching ratios – especially when considering that in order to reduce multi-jet background the final states in which the WW and ZZ were reconstructed are the leptonic ones, $WW \rightarrow e\nu\mu\nu$ (with different flavour leptons to suppress $t\bar{t}$ background; $BR \approx 2\%$) and $ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) ($BR \approx 0.4\%$). They are on the other hand the ones with the best compromise in terms of acceptance times efficiency, and signal-to-background ratio. The relatively good S/B of such modes (about 1 for $ZZ \rightarrow 4\ell$, 15% for $WW \rightarrow e\nu\mu\nu$, and 3% for $\gamma\gamma$) allowed the Higgs boson to be discovered in 2012 with only a few hundreds of candidates reconstructed (about 200 in the $\gamma\gamma$ channel, 100 in the WW channel and 5 in the ZZ channel) out of the approximately 220 thousand Higgs bosons produced in the pp collisions that were analysed. An excess with a local p -value corresponding to a significance of 5.9σ was observed by ATLAS, with – after taking into account the trial factor, also called look-elsewhere-effect – a global significance of 5.1σ . The excess in the ATLAS data pointed to a boson with a Higgs boson mass around 126 GeV, and an overall yield slightly larger – but in good agreement with – the Standard Model: the “signal strength” μ , *i.e.* the ratio between the observed and predicted cross-section times branching ratio in the hypothesis that all production and decay modes scale with the same factor, was $\mu = 1.4 \pm 0.3$.

2.3.2 Higgs boson characterisation: bosonic decays

After the discovery, the two collaborations have analysed larger datasets: first the full Run 1 sample, corresponding to about 5 fb^{-1} of 7 TeV pp collisions and 20 fb^{-1} of 8 TeV pp collisions; then the data collected in Run 2, at a center-of-mass energy of 13 TeV: 36 fb^{-1} in 2015 and 2016, and 44 fb^{-1} in 2017. Data taking in 2018 started in May and is still ongoing; no analysis of the 2018 dataset has been publicly released yet. The study of larger and larger dataset allowed the two collaborations to probe the SM predictions with better and better precision, and to search

for decay modes and production processes that are either rarer (with smaller branching ratios or production cross sections) or have worse signal-to-background ratio.

With the additional Run 1 data, the decays of the Higgs boson to diboson pairs ($\gamma\gamma$, ZZ , WW) have been each well established with a significance greater than 5σ by both the ATLAS and CMS Collaborations (see Ref. [17] and references therein). With the larger sample of 13 TeV pp collisions in Run 2 they are now the subject of precision measurements [30, 31, 32, 33, 34, 35, 36, 37, 38, 39], like those of fiducial differential cross sections. The diboson invariant mass spectra (or transverse invariant mass spectrum for the case of WW) from the latest public ATLAS analyses of 13 TeV data are shown in Figure 2.10.

The $Z\gamma$ decay channel on the other hand is not established yet. For $m_H = 125$ GeV it is expected to have a branching ratio which is about $2/3$ of the diphoton one and thus small but not negligible. However, due to trigger bandwidth limitations, only events with leptonic decays ($Z \rightarrow \ell\ell$) of the Z boson are selected, keeping only about 6.7% of the initial $H \rightarrow Z\gamma$ candidates. Moreover, the photons and leptons that are produced tend to have a rather soft p_T spectrum, and reconstruction efficiencies which are correspondingly not very high. In the end, only a few tens of signal events are selected, over a much larger background of $Z + \gamma$ and $Z + \text{jet}$ events, and no significant signal has yet been observed. The most recent results, using 36 fb^{-1} Run 2 data, are given in Refs. [40, 41]: upper limits in the range 3.9–6.6 times the Standard Model prediction are set on the $pp \rightarrow H$ production cross section times the branching ratio $BR(H \rightarrow Z\gamma)$.

2.3.3 Higgs boson characterisation: mass

The high-resolution channels, $\gamma\gamma$ and $ZZ \rightarrow 4\ell$, have been used to measure the Higgs boson mass with a precision of 0.2%, thanks to the excellent calibration of the lepton and photon momentum and energy scale, from the position of the peak due to the signal in the diphoton and four-lepton invariant mass distributions. Combining their Run 1 datasets, the ATLAS and CMS Collaborations measured the mass of the Higgs boson to be 125.09 ± 0.24 GeV [42]. With 36 fb^{-1} of Run 2 data, using the four-lepton channel, the CMS Collaboration measured the Higgs boson mass to be 125.26 ± 0.21 GeV¹ [36]. Using a similar dataset and both diphoton and four-lepton decays, and then combining the results with those based on Run 1 data, ATLAS measured the Higgs boson mass to be 124.97 ± 0.24 GeV [43].

2.3.4 Higgs boson characterisation: spin and parity

The bosonic channels, $\gamma\gamma$, $ZZ \rightarrow 4\ell$ and $WW \rightarrow \ell\nu\ell\nu$, have also been used to study the spin and parity of the Higgs boson [44, 45]. Such measurements are based on Run 1 data and on the fact that different J^P hypotheses lead to different angular distributions and correlations of the final state decay products and allow thus discriminating between the Standard Model hypothesis, $J^P = 0^+$, and various alternative hypotheses, including non-SM spin-0 and various spin-2 models (the spin-1 hypothesis is excluded due to the observation to two photons, which is forbidden for a $J = 1$ boson, and it is not possible to exclude the spin-2 hypothesis). All tested alternative models have been excluded in favour of the SM Higgs boson hypothesis at more than 99.9% confidence level.

¹the expected uncertainty is 0.26 GeV

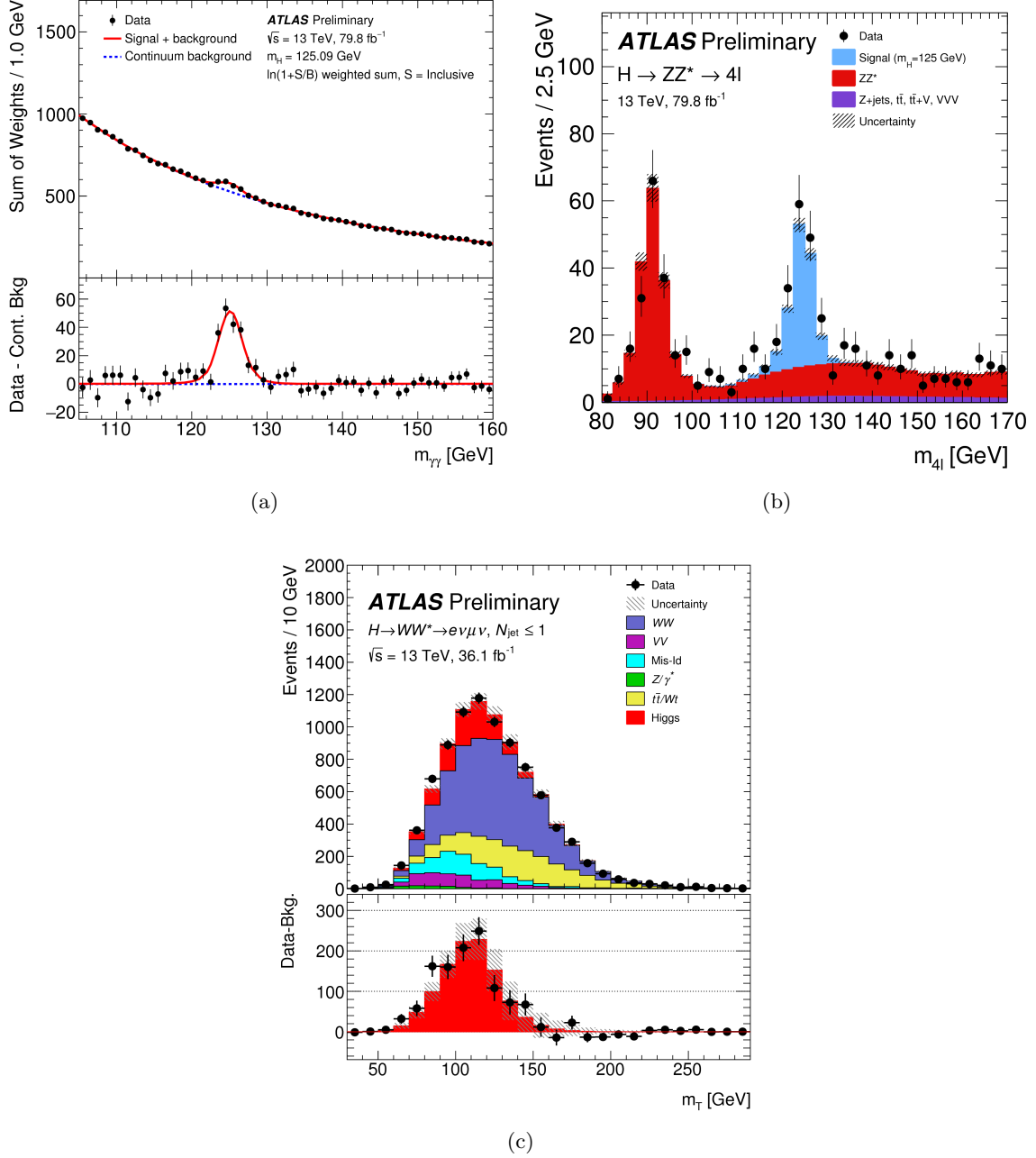


Figure 2.10 – (a) Weighted diphoton invariant mass spectrum in 80 fb $^{-1}$ of 13 TeV ATLAS data. Events are weighted by $\ln(1 + S_{90}/B_{90})$, where S_{90} (B_{90}) for each category of the analysis is the expected signal (background) in the smallest $m_{\gamma\gamma}$ window containing 90% of the expected signal. (b) Four-lepton invariant mass distributions of the $H \rightarrow ZZ \rightarrow 4\ell$ candidates selected in 80 fb $^{-1}$ of 13 TeV ATLAS data. (c) Transverse mass distribution of $H \rightarrow WW \rightarrow e\nu\mu\nu$ candidates in 36 fb $^{-1}$ of 13 TeV ATLAS data.

2.3.5 Higgs boson characterisation: fermionic decays

Concerning the decays to fermions, those to τ pairs were first established at the 5.5σ level by a combination of the ATLAS and CMS Run 1 analyses [17], and then observed with a $> 5\sigma$ significance by each Collaboration [46, 47] using 36 fb^{-1} of 13 TeV data.

The decays to bottom quark pairs are the subject of this thesis and the analysis of the 13 TeV ATLAS data to search for such decays in the VH production mode, leading to the observation of this decay mode, will be described in the following sections. The combination of the ATLAS and CMS Run 1 results lead to a small hint of such decays, with a local significance of 2.6σ . A search for $H \rightarrow bb$ decays was also performed by the Tevatron experiments, CDF and D0, in the VH associated production mode. The search was conducted for a Higgs boson with mass between 100 and 150 GeV and the results were published in August 2012 [18]. An excess of events in the di-jet invariant mass region between 120 and 135 GeV was observed in the data compared with the background predictions. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations, providing a first, despite weak, evidence of such decays.

Decays to muon pairs have been searched for but no significant signal has been observed yet, due to the small signal yield (from the small dimuon branching ratio) and the very large Drell-Yan background ($pp \rightarrow Z + X$, $Z \rightarrow \mu\mu$). Upper limits in the range 2.1–2.9 times the Standard Model prediction have been set on the $pp \rightarrow H$ production cross section times the branching ratio $BR(H \rightarrow \mu\mu)$ by the ATLAS and CMS Collaborations using between 36 and 80 fb^{-1} of 13 TeV pp collisions [48, 49].

2.3.6 Higgs boson characterisation: production modes

Higgs boson decays to a certain final state are identified by searching for the particles produced in a certain Higgs boson decay. On the other hand, the different Higgs boson production modes are identified by looking at the properties of the other particles in the events, exploiting the different kinematic properties of the various production mechanisms. VBF events produce two jets, from the scattering quarks, in opposite directions and close to the beamline. VH events either give rise to two jets with invariant mass close to that of a W or Z boson in the case of a hadronic decay of the V boson, to two charged leptons with invariant mass close to the Z boson mass for $Z \rightarrow \ell\ell$, or to zero or one charged leptons and transverse momentum imbalance from neutrinos in the case of $Z \rightarrow \nu\nu$ and $W \rightarrow \ell\nu$ decays. In $t\bar{t}H$ events the Higgs boson decay products are accompanied by two b-jets and two W bosons decaying to lepton or quark pairs, arising from the $t \rightarrow Wb$ decays. Searches for a particular production mode can be performed using several decay channels and then combined together to maximise the sensitivity.

Gluon fusion has the less distinctive signature but it has the largest cross section, as shown in Table 2.1, and was the first production mode to be unequivocally observed by both ATLAS and CMS with their Run 1 data. VBF, which has the second-largest cross section, was observed at the 5.4σ level combining the ATLAS and CMS Run 1 analyses, and then was established separately by each Collaboration using Run 2 data [50, 51]. Evidence for associated production mode with a vector boson, VH , was found by the combined ATLAS and CMS analysis of Run 1 data, at the 3.5σ level. The largest sensitivity to this production mode, which has a rather small cross section, is provided by the $H \rightarrow bb$ decay, due to its large branching ratio leading to the best compromise between the signal yield and signal-to-background ratio. The observation of the VH production mode with the ATLAS Run 2 data, mostly based on the $H \rightarrow bb$ analysis, will be described in later sections. Similarly to VH , evidence for $t\bar{t}H$ production was found by the combined ATLAS and CMS analysis of Run 1 data (at the 4.4σ level). The increase

of center-of-mass energy and the corresponding increase by a factor four of the ttH production cross section, together with a reoptimisation of the analyses, allowed both the ATLAS and CMS Collaborations to observe this production mode with a significance larger than 5σ [52, 53]. Most of the sensitivity to this production mode is provided by the so-called “multi-lepton” analysis, in which a final state with 2 same-sign leptons or three or more leptons (vetoing final states consistent with $H \rightarrow ZZ \rightarrow 4\ell$ decays) is searched for. Such final state receives contributions from $H \rightarrow WW$, $H \rightarrow \tau\tau$ and $H \rightarrow ZZ \rightarrow qql\ell$ decays. The $H \rightarrow \gamma\gamma$ decay, despite its lower signal yield, also contributes significantly to the observed signal, thanks to its smaller systematic uncertainty (unlike the multi-lepton and the bb final states, the ttH , $H \rightarrow \gamma\gamma$ analysis is statistically limited). The observation of the ttH process, together with that of the $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays, establishes the coupling of the Higgs boson to the elementary fermions of the third generation (except to ν_τ).

2.3.7 Higgs boson characterisation: overall picture

All the production mode cross sections and branching ratios that are measured are in good agreement with the Standard Model predictions. This is illustrated for instance in Figure 2.11. The global signal strength measured by ATLAS with 13 TeV data is $\mu = 1.13^{+0.09}_{-0.08}$. The signal strength for each production mode is in agreement with the SM prediction of 1, as well as the ratios of the cross sections of various production modes and of the ratios of branching ratios to different decay modes. Expressing the production cross sections and branching ratios in terms of the couplings, the couplings themselves are measured and found in good agreement with the SM predictions described in Section 2.1.3.

More fiducial measurements, as well as differential measurements [54] as for instance those shown in Figure 2.12, also exhibit good agreement with the SM predictions for a Higgs boson with a mass of 125 GeV.

2.4 Drawbacks of the Standard Model

The Standard Model can be augmented with small extensions that are still consistent with its principles, like the existence of additional generations of fermions, the presence of right-handed neutrinos, and non negligible neutrino masses.

However, the Standard Model exhibits some problems when extrapolated to very high energies, which might indicate that a new theory, of which the SM would be the low-energy approximation, should replace it [55]. They are listed below for completeness, even though this thesis focuses on the study of the Higgs boson and not on searches for beyond-Standard Model (BSM) signatures. Hints of BSM physics could anyway be found even through Higgs boson studies by observing deviations between the observed Higgs boson properties and the corresponding SM predictions.

The high-energy problems of the Standard Model are the following:

- the $U(1)$ coupling and the Higgs self-coupling tend to infinity at finite energies. It should be noted, however, that this happens at energies higher than the Planck mass (10^{19} GeV), where anyway, quantum gravity effects might be relevant.
- radiative corrections might lead at high energies (above about 10^{11} GeV) to negative values of the Higgs boson self-coupling, which would imply that the electroweak vacuum

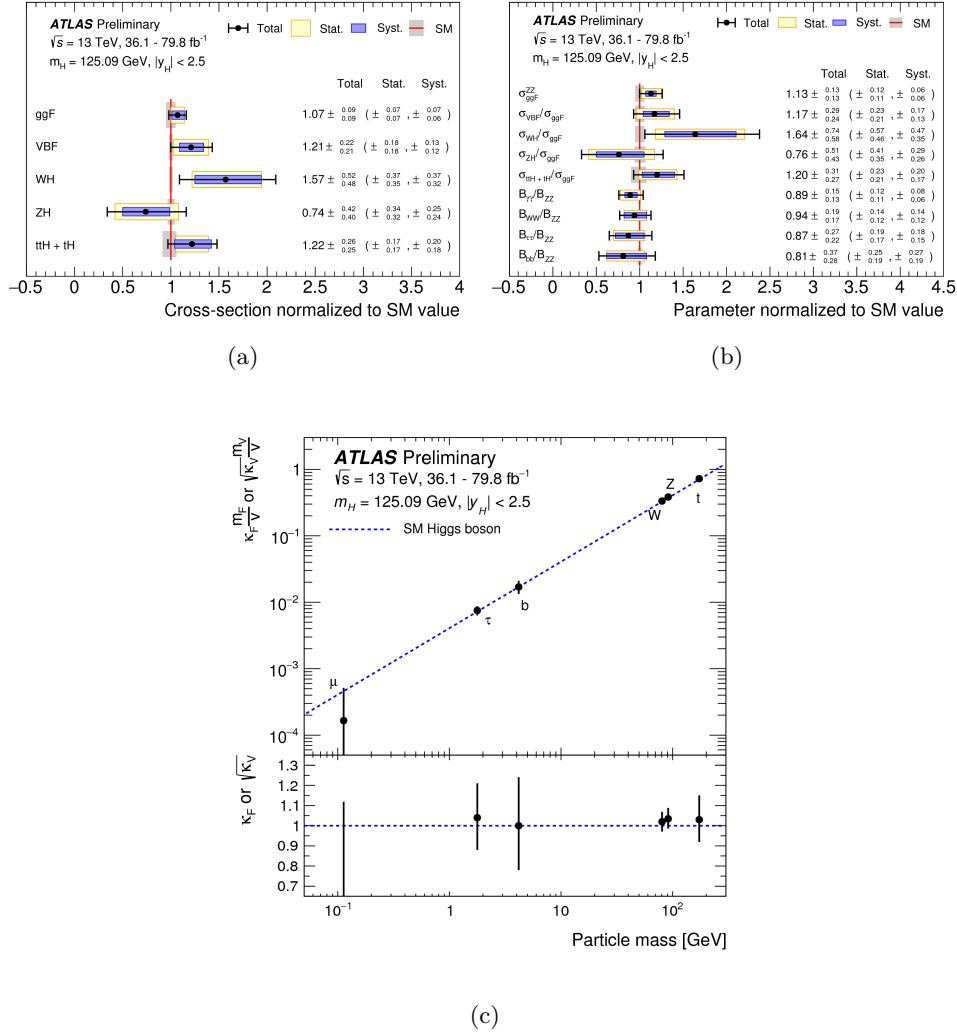


Figure 2.11 – Results of the combined analysis of several ATLAS analyses using 13 TeV pp collisions (80 fb^{-1} for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \mu\mu$, and 36 fb^{-1} for $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow bb$ and ttH , $H \rightarrow \text{multi-leptons}$). (a) Cross-sections for ggF, VBF, WH, ZH and ttH normalized to their SM predictions, measured with the assumption of SM branching fractions. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The grey bands indicate the theory uncertainties in the cross-section predictions. (b) Results of a simultaneous fit to several quantities of interest, including ratios of production cross sections and of decay branching ratios. The fit results are normalized to the SM predictions. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The grey bands show the theory uncertainties in the predictions. (c) Reduced coupling strength modifiers $k_F m_F/v$ for fermions ($F = t, b, \tau, \mu$) and $\sqrt{k_V} m_V/v$ for weak gauge bosons ($V = W, Z$) as a function of their masses m_F and m_V , respectively, and the vacuum expectation value of the Higgs field $v = 246 \text{ GeV}$. The SM prediction for both cases is also shown (dotted line). The couplings modifiers k_F and k_V are multipliers of the SM Yukawa couplings and are measured assuming no beyond-Standard Model (BSM) contributions to the Higgs boson decays, and the SM structure of loop processes such as ggF, $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$.

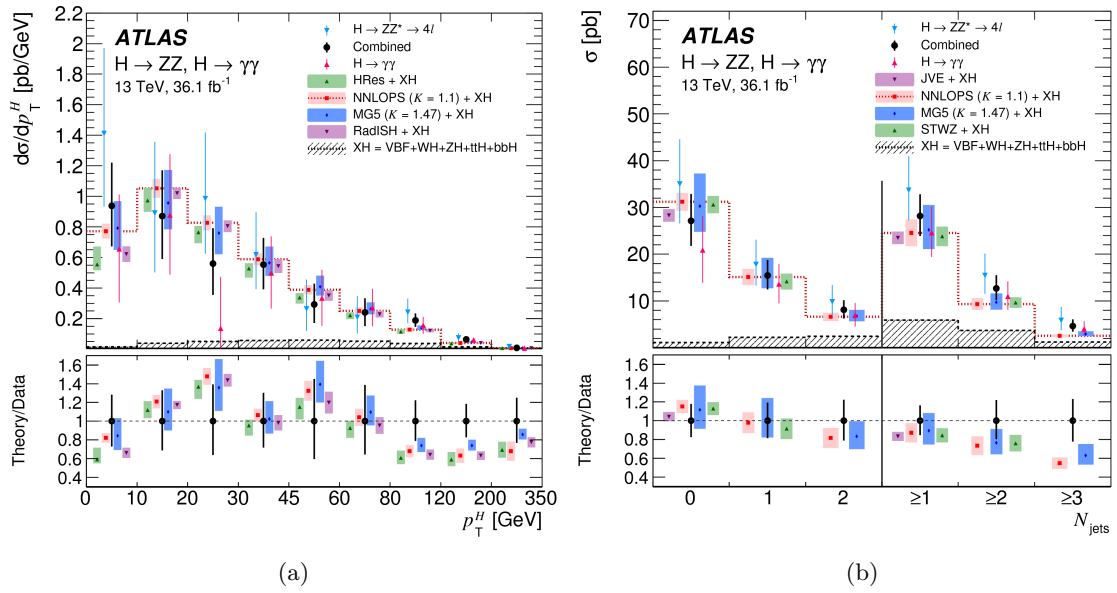


Figure 2.12 – Differential cross sections in the full phase space measured with the $H \rightarrow \gamma\gamma$ (red upward triangle) and $H \rightarrow ZZ \rightarrow 4\ell$ (blue downward triangle) decay channels, as well as the combined measurement (black circle) for (a) Higgs boson transverse momentum p_T^H , and (b) number of jets N_{jets} with $p_T > 30$ GeV, using 36 fb $^{-1}$ of 13 TeV pp collisions collected by ATLAS. Different SM ggF predictions are overlaid, their bands indicating the PDF uncertainties as well as uncertainties due to missing higher-order corrections. Predictions for the other production processes XH are added to the ggF predictions, and also shown separately as a shaded area. The panel on the bottom shows the ratio of the predictions to the combined measurement. The total uncertainties of the combined measurement are indicated by the black error bars.

is unstable or metastable. This however depends on the exact value of the top mass and on the order of accuracy of the perturbative calculation, and the energy where λ becomes negative could reach the Planck scale with more accurate calculations and new determinations of the top mass that favour lower values than current measurements.

- the Higgs boson mass seems to be “unnaturally” small with respect to its bare mass. The Higgs boson mass is the result of the addition of a bare mass term m_0 and of radiative corrections induced by the couplings of the Higgs boson to the other particles. Considering the dominant terms:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2} \left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2 \right) \Lambda^2 \quad (2.25)$$

$$= m_0^2 - (115 \text{ GeV})^2 \left(\frac{\Lambda}{400 \text{ GeV}} \right)^2, \quad (2.26)$$

where Λ is the energy scale that limits the SM validity. If the SM is valid up to the Planck scale, then the bare mass and the radiative correction terms would need to cancel to a level of 10^{-35} , pointing to an extremely large fine tuning of the bare mass. This problem can disappear if there is some new physics at an energy scale Λ much lower than the Planck scale, or if there are extra particles (as in Supersymmetry) that introduced radiative corrections that counterbalance, at least to some extent, those from the SM particles.

The Standard Model also raises some fundamental questions that are left with no answer:

- why is its symmetry group $SU(3) \otimes SU(2) \otimes U(1)$?
- why are there 3 generations of fermions?
- is there a reason for the quark-lepton symmetry?
- why left-handed and right-handed fermions behave so differently?
- why do charged-current weak interactions have a $V - A$ structure?
- are baryon and lepton numbers conserved by accident or is there some symmetry that preserves them from being violated?

Other questions with unclear answers include how neutrinos get masses, how confinement works, how to explain the observed level of matter-antimatter asymmetry in the Universe, and what is dark matter.

The solutions explored by theoretical physicists proceed in four directions: extending the symmetry group of the Standard Model, extending its particle content, extending the number of spatial dimensions, or replacing the SM with a non-local theory like string theory. So far there are no clear indications whether one of these approaches is the correct one, and more experimental data are needed to guide the investigations.

Chapter 3

The ATLAS Experiment at the LHC

ATLAS (A Toroidal LHC Apparatus) [10] is a multipurpose high-energy physics experiment designed and built to study the results of the collisions between protons or heavy ion bunches accelerated by the Large Hadron Collider (LHC) [56]. In the following sections, a description of the LHC and of the ATLAS detector are given.

3.1 The Large Hadron Collider

The Large Hadron Collider is a proton and heavy ion collider at CERN. It is located in the 26.7 km long, 100 m deep tunnel previously used by the LEP e^+e^- collider. Proton beams were chosen for the LHC instead of electrons as at LEP in order to reach higher energies (nominally 7 TeV per beam instead of a maximum of 104.5 GeV as at LEP) while limiting synchrotron radiation.

3.1.1 Proton acceleration in the LHC

Proton bunches are injected into the LHC after having passed through a chain composed of four other accelerators, as shown in Figure 3.1: a linear accelerator (LINAC), the “proton synchrotron booster” (PSB), the “proton synchrotron” (PS), and the “super proton synchrotron” (SPS), which raise gradually the proton energy to 50 MeV, 1.4 GeV, 25 GeV and 450 GeV, respectively.

The bunches are injected in opposite directions in the LHC and accelerated by the radiofrequency cavities to the final nominal energy $\sqrt{s}/2$. So far the best achieved beam energy value, limited by the operational stability of the bending dipole magnets described below, is $\sqrt{s}/2 = 6.5$ TeV. The cavities are superconducting and operate at a temperature of 4.5 K.

To keep the protons along their trajectory, 1232 bending dipole magnets, 14.3 meters long each, are installed along the LHC. The dipoles are made of superconducting niobium-titanium coils operating at a temperature of 1.9 K. In order to keep constant the radius of curvature of the proton trajectory, the dipole magnetic field is increased proportionally to the proton energy, from 0.5 T at 450 GeV to 7.7 T at 6.5 TeV (and 8.3 T when the protons will be accelerated to the design value of 7 TeV).

Several quadrupole magnets are also installed along the beam pipe, focusing the beams alternatively in the horizontal and in the vertical plane, depending on their polarity.

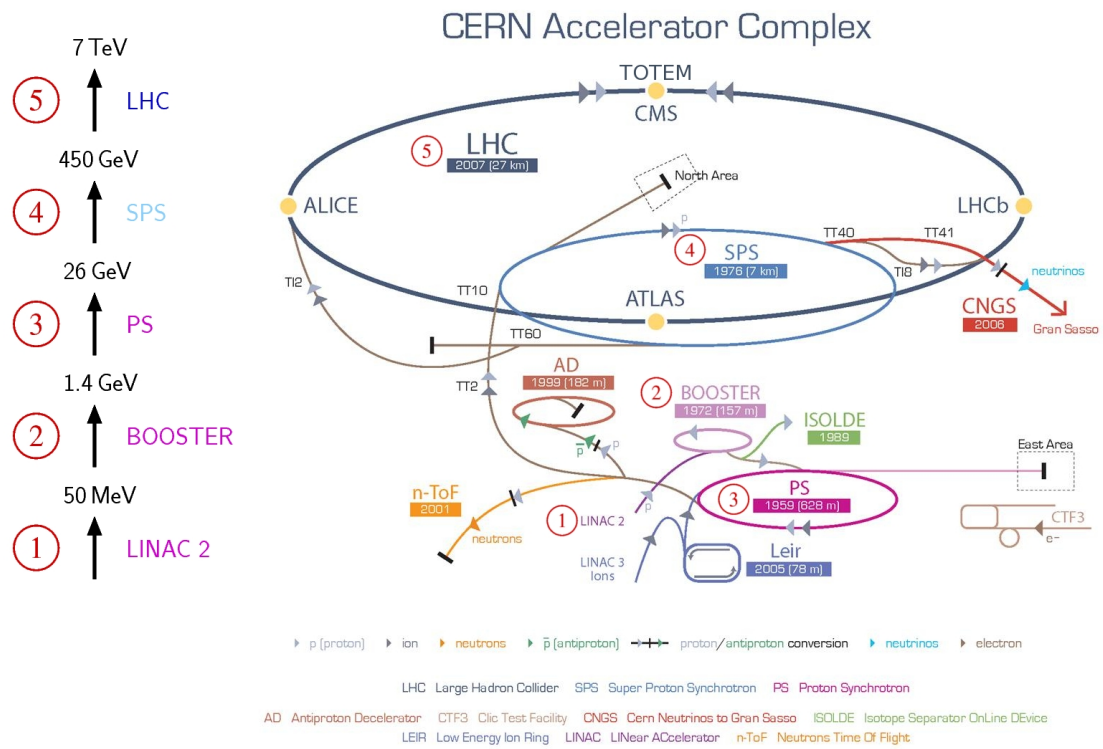


Figure 3.1 – Representation of the different steps, within the CERN accelerator complex, necessary to inject protons in the LHC ring.

3.1.2 Proton collisions in the LHC

Protons circulates in opposite directions in two separate beam pipes, which cross in a few “interaction points” (IP), where the bunches collide, and around which the LHC experiments were built. They are:

- ATLAS and CMS (Compact Muon Solenoid), two general purpose detectors that study the high-intensity, high-energy proton and heavy-ion collisions;
- LHCb, a detector focusing on precision measurements of the flavor and CP sector of the Standard Model and on new physics searches with rare B meson decays;
- ALICE, a detector for the study of strong interactions and of quark-gluon plasma produced in heavy ion collisions.

Two additional detectors, TOTEM and LHCf, dedicated to the study of soft proton collisions yielding scattered particles in the forward direction close to the beam pipe, were installed near the CMS and ATLAS detectors, respectively. A third small detector, MoEDAL, was installed in the LHCb cavern and is designed to search for highly ionizing particles predicted by new physics scenarios such as magnetic monopoles.

In the interaction region the two beam pipes merge into a single vacuum chamber. The proton beams do not collide head-on to avoid significant long-range electromagnetic interactions between the bunches far away from the nominal interaction point. A small crossing angle of about two hundred microradians is used instead. To recover some (around 5%) of the total potential luminosity that gets lost since the beams do not collide head-on, the crossing angle is progressively reduced during a run, as the number of protons in each bunch decrease due to their collisions.

The protons are injected in the LHC and accelerated in bunches. Each bunch is about 9 cm long and contains around 100 billion protons. The bunches are kept separated by about 7.5 m, meaning – given that the proton speed is close to the speed of light¹ – that the collisions take place every 25 ns. The length of the LHC tunnel (26659 m) could thus accommodate 3554 bunches; however, some of these so-called “buckets” are kept empty to create an “abort gap” which is needed for safe beam dumps. This is due to the significant time to switch on the magnets which divert the beam from the LHC into the dump. The (maximum) number of occupied buckets in the LHC is thus 2808, while the maximum number of bunches injected in the LHC so far is 2544, limited by small technical issues in the injection from the SPS that will be fixed for the LHC Run 3.

The LHC operates in “physics fills”. In a fill, protons are accelerated by the chain upstream of the LHC and then injected in the LHC, where they are focused and brought to the final collision energy. This process takes about twenty minutes. The proton orbits are then adjusted to make the proton beam collide, and data taking in the LHC experiments starts. As the protons in the bunches collide and are removed from the beams, the instantaneous luminosity

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

¹At their designed energy of 7 TeV, the particles in the LHC will travel at 0.999999991 the speed of light

decreases. In the previous formula,

- N_b is the number of protons in each bunch ;
- n_b is the number of bunches;
- f_{rev} is the bunch revolution frequency ($c/2\pi R = 11.245$ kHz);
- γ_r is the Lorentz boost factor;
- ϵ_n is the normalised transverse beam emittance, which characterises the average spread of the beam in the position-and-momentum phase space;
- β^* is the value of the beta function (which quantifies the transverse beam size) at the collision point;
- F is a geometric luminosity reduction factor due to the beam crossing angle.

Collisions among protons take place at a rate $-\frac{dN_b}{dt} = \mathcal{L}\sigma_{\text{tot}}$, where $\sigma_{\text{tot}} \approx 100$ mb is the total pp cross section. As a consequence, and taking into account the number $k = 4$ of interaction points, the luminosity decreases with time as

$$\mathcal{L}(t) = \frac{\mathcal{L}(t=0)}{\left(1 + \frac{t}{\tau}\right)^2}. \quad (3.2)$$

The beam lifetime τ is

$$\tau = \frac{n_b N_b(t=0)}{\mathcal{L}(t=0)\sigma_{\text{tot}}k} \quad (3.3)$$

which, for $N_b(t=0) = 10^{11}$ and the design luminosity $\mathcal{L}(t=0) = 10^{34} \text{cm}^{-2}\text{s}^{-1}$, is equal to about 20 hours. Other processes, like inelastic scattering of the protons on the residual gas molecules of the beam pipe “vacuum”, reduce the beam lifetime. After several hours from the start of the fill, when the instantaneous luminosity becomes too small, the beams are dumped, and a new fill takes place. To increase the instantaneous luminosity, as already mentioned, the crossing angle between the proton beams is gradually reduced. A second expedient that is used to maximise the integrated luminosity (*i.e.* the integral over time of the instantaneous luminosity) is the increase of the focusing of the beams (β^*) when the end of the fill approaches.²

3.1.3 History of the LHC and evolution of the beam parameters

The LHC was approved by the CERN Council in December 1994 and built in the following 15 years. It started operations in 2009. The design values of the main parameters of the LHC, as well as the values obtained so far, are summarised in Table 3.1.

²the gain in integrated luminosity from this trick is quite marginal in Run 2 but it provides the proof-of-concept of a technique that will be more important in Run 3 and later on.

Table 3.1 – Typical beam conditions at the LHC during pp collisions from 2010 to 2017, together with the design parameters.

Machine parameter	Design	2010	2011	2012	2015	2016	2017
Beam energy [TeV]	7.0	3.5	3.5	4.0	6.5	6.5	6.5
N_b [10^{11} p]	1.15	1.0	1.3	1.5	1.0	1.1	1.2
n_b	2808	368	1380	1380	2244	2200	2544
Bunch spacing [ns]	25	150	50	50	25	25	25
f_{rev} [kHz]	11.245	11.245	11.245	11.245	11.245	11.245	11.245
ϵ_b [μm]	3.75	2.6	2.4	2.4	3.5	2.2	2.3
β^* [m]	0.55	3.5	1.0–1.5	0.6	0.8	0.4	0.3
Max. peak luminosity [10^{34} $\text{cm}^{-2} \text{s}^{-1}$]	1.0	0.021	0.36	0.77	0.47	1.45	1.7

The first LHC pp collisions took place at the end of 2009, first at a center of mass energy $\sqrt{s} = 900$ GeV, and later at $\sqrt{s} = 2.36$ TeV. This short “commissioning” run was followed in 2010–2012 by the first high-intensity “physics” run, known as the LHC Run 1.

In 2010 and 2011, protons were accelerated to an energy of 3.5 TeV per beam ($\sqrt{s} = 7$ TeV). In 2012, the beam energy was increased to 4 TeV ($\sqrt{s} = 8$ TeV).

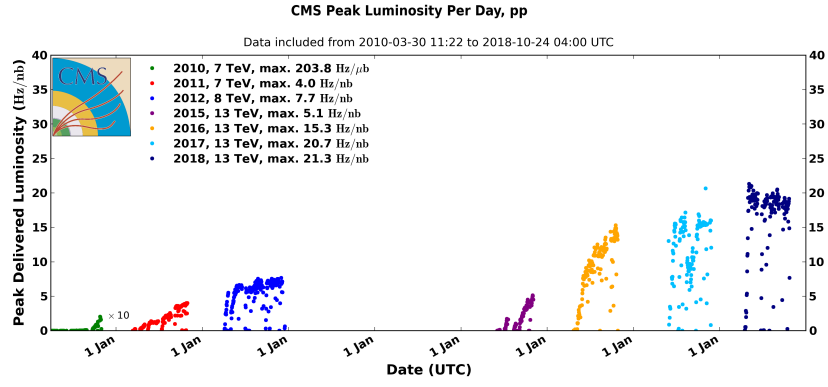
In 2013 and 2014, the LHC was shut-down to allow for consolidation activities to improve the accelerator reliability, including the replacement of a few dipole magnets, and improvements of the quench protection system, of the connections between the dipoles, of the cryogenics and of the vacuum inside the beam pipe. This made it possible to operate the radio-frequency cavities at higher voltages, allowing the protons to be accelerated to 6.5 TeV in the LHC Run 2, that started in 2015 and is still ongoing.

Over the years the instantaneous peak luminosity has been steadily increasing, as seen in Figure 3.2a. In 2010, the luminosity was rapidly increased from about $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ to $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, limited by the small number of bunches (368) and the quite large β^* (3.5 m). In 2011, thanks to a 30% larger number of protons in the bunches, almost four times more bunches in the beams (1380 bunches separated by 50 ns), and better focusing of the beams ($\beta^* = 1$ m), the peak instantaneous luminosity was $3.65 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. In 2012, further increase (+15%) in the number of protons per bunches and squeeze of the beams ($\beta^* = 0.6$ m) led to a peak luminosity of $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. In Run 2, the doubling of the proton bunches, separated in time by the design value of 25 ns, and a further reduction of β^* (0.4 m in 2016) made it possible to exceed the LHC design luminosity value, reaching peak luminosities of $1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2016, $1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2017, and $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2018.

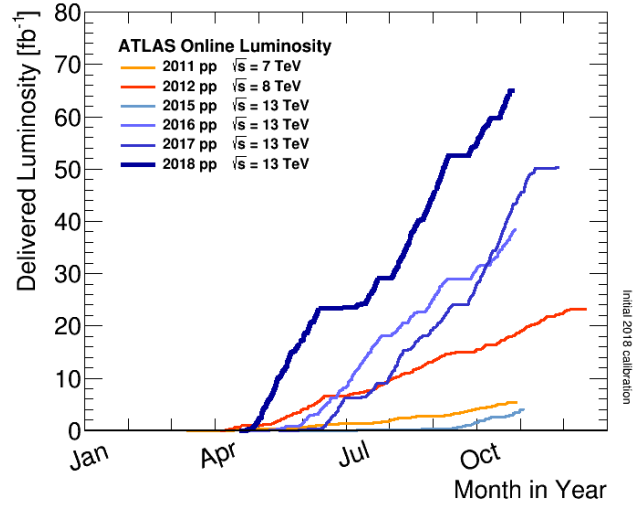
The total integrated luminosity delivered to ATLAS (Figure 3.2b) was about 5.6 fb^{-1} at $\sqrt{s} = 7$ TeV in 2010–2011, and 23.3 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. In Run 2, at $\sqrt{s} = 13$ TeV, the luminosity delivered to ATLAS was 4.2 fb^{-1} in 2015, 38.5 fb^{-1} in 2016, 50.2 fb^{-1} in 2017, and 61.2 fb^{-1} in 2018.

3.2 The ATLAS detector

The ATLAS detector is built around one of the four LHC interaction points. It has a cylindrical shape, with its axis coinciding with the beam pipe. It is the largest of the LHC detectors, having a radius of 12 m and a length of 44 m. Its weight is around 7000 tons. To cover a large fraction of the solid angle, ATLAS is composed of a central “barrel” section that detects particles produced at large angles with respect to the beam direction, and two “end-



(a)



(b)

Figure 3.2 – (a) Peak luminosity delivered to CMS (and similarly to ATLAS) and (b) integrated luminosity delivered to ATLAS during stable beams for pp collisions.

cap” sections that detect particles produced more closely to the beams. A sketch of the ATLAS detector is given in Figure 3.3.

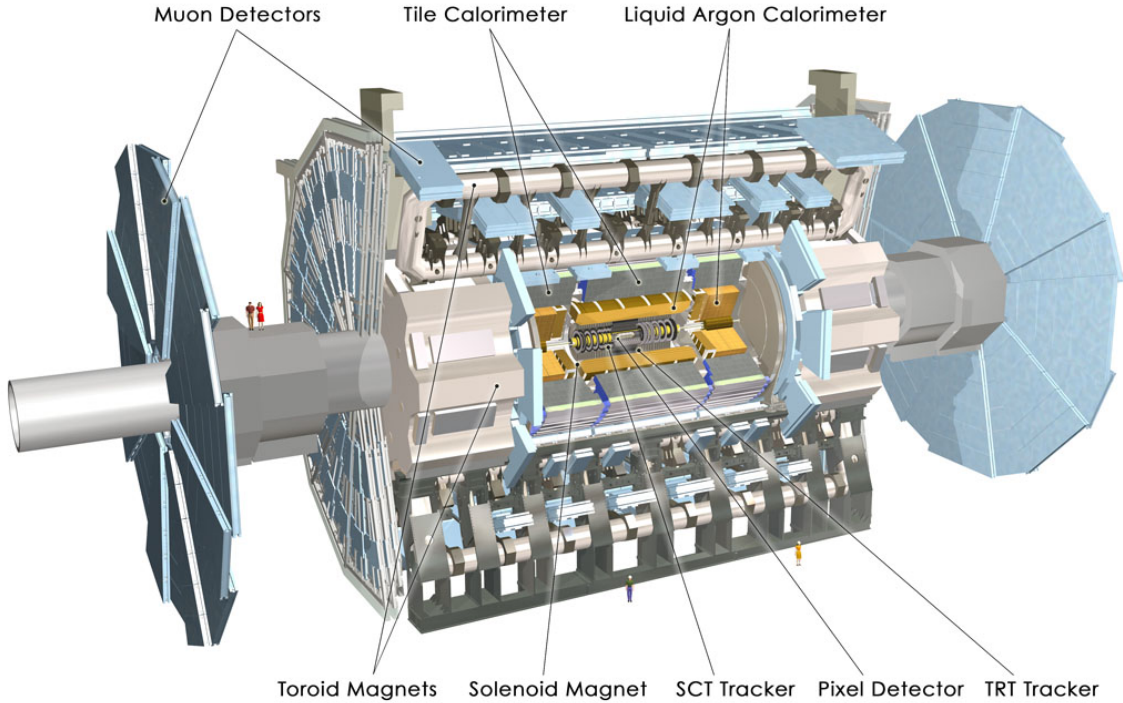


Figure 3.3 – Overview of the ATLAS detector.

To reconstruct the different particles produced in the pp and heavy-ion collisions, ATLAS uses three nested subsystems, based on different detection principles and technologies:

- the Inner Detector (ID) measures the trajectory and the momentum of charged particle tracks and reconstructs interaction vertices;
- the calorimeter, composed of an inner electromagnetic (EM) section and an outer hadronic (HAD) compartment, absorbs electrons, photons and hadrons, and measures their energy deposition and direction;
- the Muon Spectrometer (MS) reconstructs tracks from muons that pass through the calorimeter and provides a second measurement, which is useful for muon with high p_T , of their momenta in addition to the one from the ID.

The momentum measurement in the ID and in the MS relies on the presence of a magnetic field generated by a system of magnets:

- a superconducting solenoid, 5.8 m long and with radius $1.23 < R < 1.28$ m, generates a 2 T axial magnetic field in which the Inner Detector is immersed. A current of 8 kA flows in the coil of the solenoid, which is operated at a temperature of 4.5 K.

- three superconducting air-core toroids, two in the end-caps and one in the barrel, each with eight coils, generate a magnetic toroidal field. The barrel toroid, with a current of 20 kA, is 25.3 m long and has inner and outer diameters of 9.4 m and 20.1 m, respectively. It generates a magnetic field of about 0.5 T. The end-cap toroids are 5.0 m long and have inner and outer diameters of 1.7 m and 10.7 m, respectively. They produce a magnetic field around 1 T.

3.2.1 The ATLAS coordinate system

ATLAS uses a right-handed coordinate system:

- The origin is the nominal interaction point (IP) in the center of the detector.
- The z -axis coincides with the beam pipe.
- The x -axis points from the IP to the center of the LHC ring.
- The y -axis points upward.

In the transverse (*i.e.* x - y) plane cylindrical coordinates (r, ϕ) are used, where ϕ is the azimuthal angle around the beam pipe. The pseudorapidity η is related to the polar angle θ :

$$\eta = -\ln \tan(\theta/2). \quad (3.4)$$

The transverse momentum p_T is defined as the transverse component of the three-dimensional momentum vector. For particles reconstructed in the calorimeter, for which a measurement of their energy E is available, the transverse energy E_T is also sometimes used, and is defined as $E_T = E \sin \theta = E / \cosh \eta$.

The three-dimensional angular distance between two vectors with pseudorapidity and azimuthal separation $\Delta\eta$ and $\Delta\phi$ is defined as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (3.5)$$

3.2.2 The Inner Detector

The Inner Detector, illustrated in Figure 3.4, is the closest of the ATLAS sub-detectors to the beam pipe. It reconstructs the trajectories and measures the momenta of the charged particles that are bent by the 2 T axial magnetic field produced by the central solenoid. It also reconstructs primary (collision) and secondary (decay) vertices. The ID has a barrel and two end-caps section, with full acceptance in ϕ and pseudorapidity coverage up to $|\eta| = 2.5$.

Three sub-systems compose the ID. Given the high density of tracks per event, high granularity silicon detectors are used in the innermost part. More cost-effective gaseous detectors with worse granularity but low mass and large number of samplings are used in the outer part of the ID. Going from the innermost one to the outermost one the three ID sub-systems are the following.

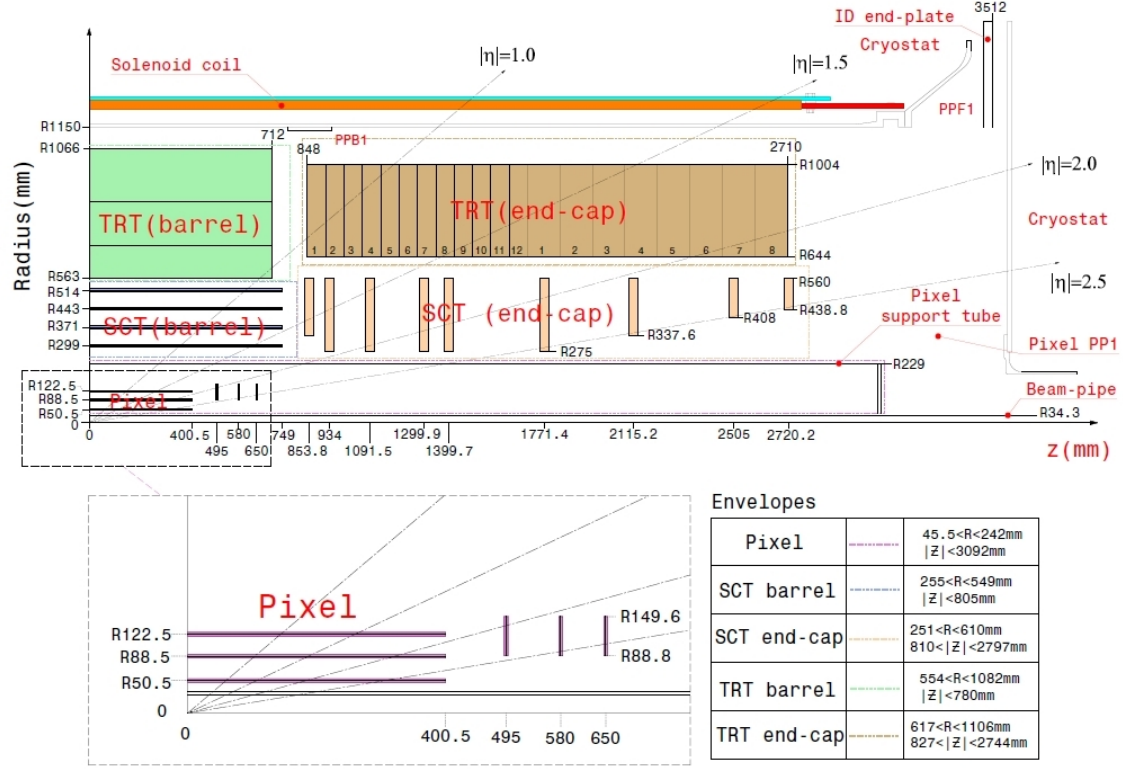


Figure 3.4 – Illustration of the ATLAS Run-1 Inner Detector.

- The silicon pixel detector covers the pseudorapidity region $|\eta| < 2.5$. In the barrel, the silicon pixel sensors are arranged in four cylindrical layers at radial distances of 31 mm, 50.5 mm, 88.5 mm and 122.5 mm from the z axis. In the end-caps the sensors are arranged in three disks, located at radial distances of 49.5 mm, 58.0 mm and 65.0 mm. The pixel detector typically provides four three-dimensional hit information for charged particles that traverse it.

The innermost barrel layer, called “insertable b-layer” (IBL), is installed in ATLAS during the shutdown between Run 1 and Run 2 [57]. The IBL was located between a new, smaller, beam pipe (radius of 27 mm instead of 30 mm as in Run 1) and the first layer of the Run 1 pixel detector. The addition of an extra layer of silicon pixels, closer to the interaction point, has led to an improvement of the tracking and secondary vertex reconstruction efficiency, which has more than compensated the degradation of performance from radiation damage and small hardware failures.

The pixel sensors have a cell size of $50 \times 250 \mu\text{m}^2$ in the IBL and $50 \times 400 \mu\text{m}^2$ elsewhere, providing an intrinsic hit position resolution of about $12 \mu\text{m}$ in the coordinate along the short side of the pixel and of about $72 \mu\text{m}$ or $115 \mu\text{m}$ for the other coordinate (respectively for the IBL and for the other layers). In the barrel, the long side of the pixel is oriented along the z axis.

- The silicon strip detector (SCT) is located at radial distances between 275 mm and 560 mm from the z axis and covers the pseudorapidity region $|\eta| < 2.5$. Single-sided silicon mi-

crostrip sensors are used to form eight cylindrical layers in the barrel region and nine layers in the end-caps. Each layer provides a two-dimensional position information.

The barrel layers are grouped in four pairs of cylinders with the two layers glued back-to-back and having slightly different orientations (40 mrad stereo angle) in order to provide three-dimensional hit reconstruction. The four barrel cylinders are located at radii of 30, 37, 44 and 51 cm from the z axis.

The strip pitch of 80 μm and the stereo angle provide intrinsic spatial resolutions of about 16 μm and 580 μm on the two coordinates being measured ($r - \phi$ and z in the barrel).

- the transition-radiation gaseous tracker (TRT) is located at radial distances between 563 mm and 1066 mm from the z axis and covers the pseudorapidity region $|\eta| < 2.0$. It uses straw tubes filled with a xenon (Xe) gas mixture (about 70% Xe, 27% CO₂ and 3% O₂). The tubes have a diameter of 4 mm and lengths up to 150 cm. The barrel section is composed of 73 layers of straw tubes, parallel to the beam line and interleaved with polypropylene fibers. The end-caps are composed of 160 layers each of straw tubes along the radial direction and interleaved with polypropylene foils.

The position information for charged particles is provided by the electric signals induced from the ionisation of the gas. The TRT only provides $r - \phi$ information in the barrel and $z - \phi$ information in the end-caps. The intrinsic, single-hit spatial resolution is 130 μm . However, the longer path length and the larger number of hits (typically 32) for charged particle tracks in the TRT compared to the silicon devices lead to a momentum resolution which is competitive with that of the silicon pixel and strip detectors.

Due to the different dielectric constant between the straw tubes and the interleaved fibers or foils, highly relativistic ($\gamma \gtrsim 10^3$) particles emit transition X-rays when they traverse the boundaries between the tubes and the material in the gaps. The X-ray photons thus produced are absorbed by the gas inside the straw tube and lead to a larger signal, which can be used to discriminate electrons from pions up to momenta of about 100 GeV. The choice of xenon as the gas for the straw tubes was motivated by the large absorption cross section of X-ray photons. Starting in 2012 a gradually increasing number of Xe leaks has started to develop in the TRT. Some modules have then been filled with a significantly cheaper argon (Ar) based gas mixture. Argon, however, has a ten times lower X-ray absorption cross section than xenon, leading to a slight decrease of the electron/pion discriminating power of the TRT.

3.2.3 The calorimeter

The ATLAS calorimeter system includes an electromagnetic calorimeter and a hadronic calorimeter. An illustration of the calorimeter system is shown in Figure 3.5. The two sections of the calorimeter are described in the following subsections.

3.2.3.1 The electromagnetic calorimeter

The energy and the position of the electromagnetic showers induced by photons and electrons³ with $|\eta| < 3.2$ are measured by a high-granularity lead/liquid-argon (LAr) sampling elec-

³in the following we do not distinguish between electrons and positrons unless stated otherwise

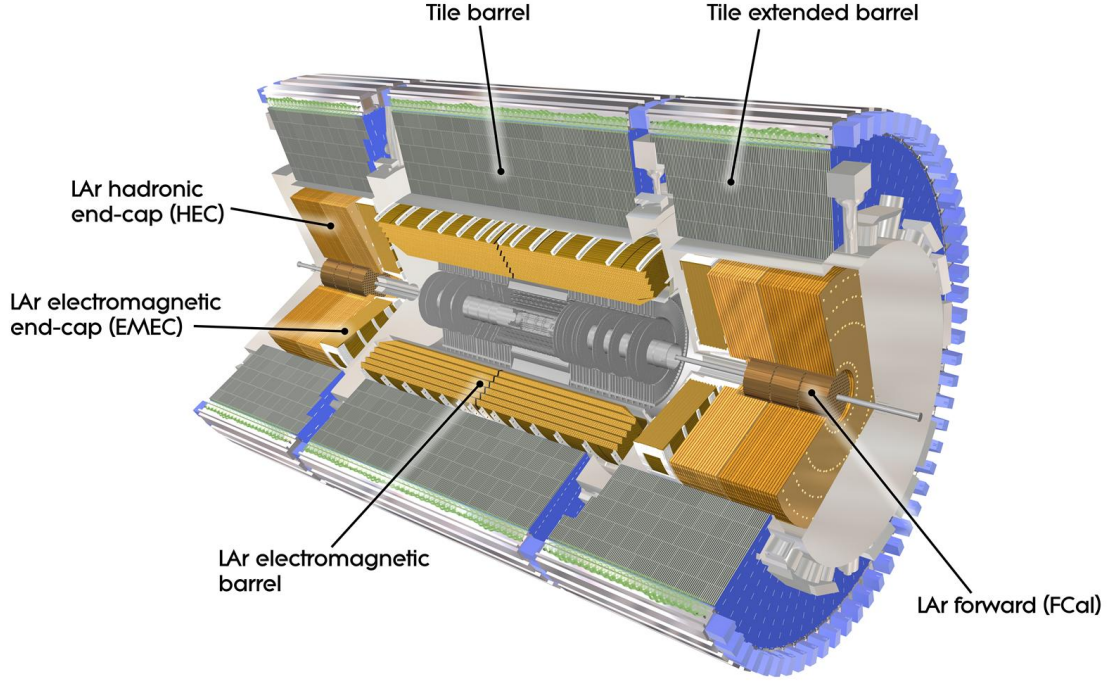


Figure 3.5 – Illustration of the ATLAS calorimeter system.

Electromagnetic calorimeter with lateral and longitudinal segmentations. The EM calorimeter is composed of a barrel section ($|\eta| < 1.475$) and of two end-cap sections ($1.375 < |\eta| < 3.2$). The barrel section is 6.4 m long, with inner and outer radii of 1.4 m and 2 m, respectively. The end-cap sections are 63 cm thick wheels, with internal and external radii of 330 mm and 2098 mm, respectively. Each end-cap wheel consists itself of two co-axial wheels, an inner one ($2.5 < |\eta| < 3.2$) and an outer one ($1.375 < |\eta| < 2.5$).

The EM calorimeter has three longitudinal sampling layers for $|\eta| < 2.5$ and two layers for $2.5 < |\eta| < 3.2$. The first layer has a thickness of up to 6 radiation lengths (X_0), including about $1.6 X_0$ of dead matter upstream of the active part of the calorimeter. In the pseudorapidity regions $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$ it is segmented into high-granularity “strips”. The strip size is 0.1 along ϕ and between 0.003 and 0.006 along η . The narrow width in η permits to discriminate between single photon EM showers and two overlapping EM showers from a $\pi^0 \rightarrow \gamma\gamma$ decay. The second layer has a thickness of about $17 X_0$ and thus collects most of the energy deposited by electrons and photons with momenta up to 50 GeV. The cell granularity in $\eta \times \phi$ is 0.025×0.025 . The third layer has a thickness varying between 4 and $15 X_0$ and a cell granularity in $\eta \times \phi$ of 0.050×0.025 . It collects the tails of the electromagnetic shower, allowing an estimate of the energy leaking in the hadronic calorimeter, and provides an additional point to reconstruct the shower barycenter.

An illustration of a barrel module of the ATLAS electromagnetic calorimeter is given in Figure 3.6. The absorbers and the electrodes have an accordion geometry to provide full coverage in ϕ . The absorbers are made of lead plates, with thickness between 1.13 mm and 2.2 mm depending on $|\eta|$. The readout electrodes are placed in the gaps between the absorbers. They are made of three layers of copper, separated by insulating polyimide sheets. A nominal high

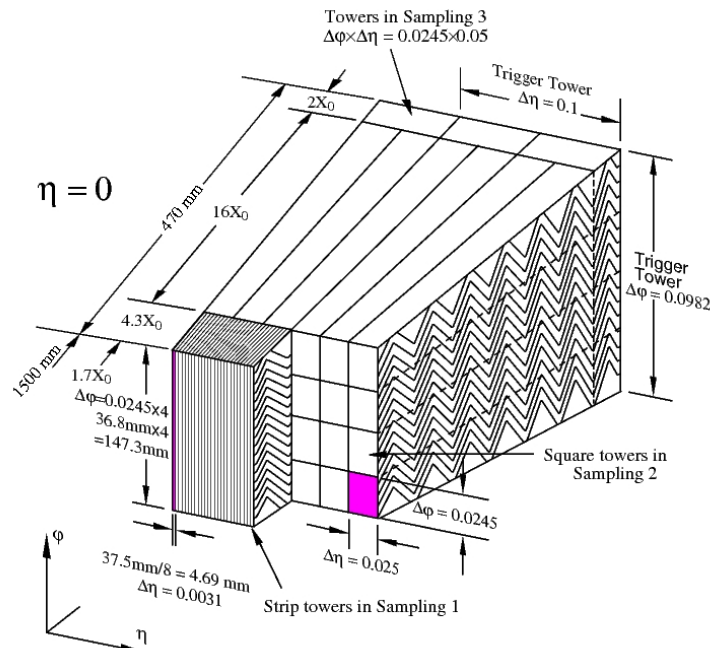


Figure 3.6 – Illustration of a barrel module of the ATLAS electromagnetic calorimeter.

voltage potential (typically around 2 kV) is applied to the two outer layers, and the signal induced on the inner layer at ground potential is read out.

The region $|\eta| < 1.8$ is instrumented with an additional thin (11 mm) liquid argon layer used as a presampler, installed inside the solenoid, upstream of the accordion calorimeter. The read-out granularity of the presampler is 0.025×0.1 in $\eta \times \phi$.

The total active thickness of the electromagnetic calorimeter ranges between $22 X_0$ and $33 X_0$ in the barrel and between $24 X_0$ and $38 X_0$ in the end-caps, and the longitudinal leakage (i.e. the fraction of shower energy that is lost) beyond the end of the active detector of electromagnetic showers initiated by photons and electrons with transverse momentum below 300 GeV is $\ll 1\%$.

3.2.4 The hadronic calorimeter

The EM calorimeter is surrounded by the hadronic calorimeter, which measures hadronic showers using either steel-scintillator tiles in the central region ($|\eta| < 1.7$) or LAr sampling calorimeters in the end-caps ($1.5 < |\eta| < 3.2$, copper absorber) and forward ($3.1 < |\eta| < 4.9$, copper-tungsten absorber) regions.

The tile calorimeter is a sampling calorimeter using steel as the absorber and a polystyrene scintillator as the active medium. It is composed of a 5.8 m-long central barrel and of two 2.6 m-long extended barrels. The inner radius is 2.28 m and the outer radius is 4.25 m, leading to a thickness of approximately 7.4 interaction lengths (λ). The scintillating tiles are 3 mm thick. Wavelength-shifting fibers on the tile edges are used to extract the scintillation light which is then read out with photomultiplier tubes. The readout granularity is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two longitudinal layers (5.6λ) and 0.2×0.1 in the third last layer (1.8λ).

The hadronic end-cap calorimeter (HEC) is a sampling calorimeter using copper as absorber and LAr as the active medium. It consists of two wheels in each end-cap, a front wheel and a

rear wheel. The modules of the front wheels are made of 24 copper plates, each 25 mm thick, plus a 12.5 mm thick front plate. The modules of the rear wheels are made of 16 copper plates, each 50 mm thick, plus a 25 mm thick front plate. The gap between the plates is 8.5 mm thick and houses four separate LAr drift zones of 1.8 mm width each, separated by three electrodes. The granularity of the HEC cells is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ or 0.2×0.2 depending on η .

The forward calorimeter (FCal) is a sampling calorimeter using copper or tungsten as absorber and LAr as the active medium. It covers the pseudorapidity region $3.1 < |\eta| < 4.9$ and is composed of two end-cap sections located in the same cryostats as the HEC. The FCal has three longitudinal layers, an “electromagnetic” layer (FCal1) with copper absorbers ($28 X_0$, 2.7λ), and two “hadronic” layers (FCal2, FCal3) with tungsten absorbers ($180 X_0$, 7.3λ). The electrodes are co-axial copper rods and copper tubes separated by a LAr gap, with width varying between 0.27 and 0.51 mm depending on the layer. The LAr gap width is smaller than in the electromagnetic calorimeter to produce faster signals and to avoid ion build-up problems due to the high particle fluxes at large η . The electrodes are located in holes drilled inside stacks of absorber plates.

3.2.5 The muon spectrometer

The muon spectrometer (Figure 3.7) exploits the bending of the muon trajectories by the magnetic field generated by the toroidal magnets to measure the momenta of muons passing through the upstream subdetectors. Muon tracks are reconstructed by a system of precision tracking chambers over the pseudorapidity region $|\eta| < 2.7$. Monitored drift tube (MDT) chambers are used, except for the innermost end-cap layer, where cathode-strip chambers (CSC) are used for $2.0 < |\eta| < 2.7$ due to their higher rate capability and time resolution. In addition, for triggering purposes, resistive plate chambers ($|\eta| < 1.05$) or thin-gap chambers ($1.05 < |\eta| < 2.4$) with time resolution better than 4 ns are also installed.

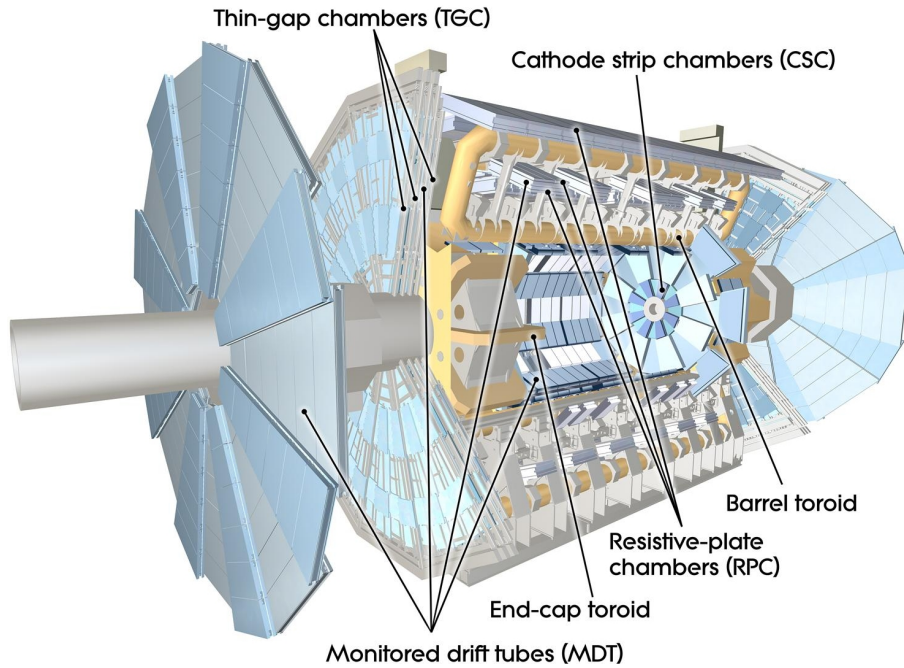


Figure 3.7 – Illustration of the ATLAS muon spectrometer.

The MS is composed by a barrel section and two end-cap sections. The precision-tracking chambers in the barrel region are located between and on the eight coils of the superconducting barrel toroid magnet. They are arranged in three coaxial cylinders at radial distances of about 5 m, 7.5 m, and 10 m from the beam axis. The end-cap chambers are in front and behind the two end-cap toroid magnets. They are arranged in large wheels, perpendicular to the z axis and located at distances of $|z| \approx 7.4$ m, 10.8 m, 14 m, and 21.5 m from the nominal interaction point. In the center of the detector ($|\eta| < 0.1$) there is a small gap to let the services of the inner components of ATLAS to pass through.

The readout pitch and geometrical orientation of the precision tracking chambers lead to a spatial resolution of about $35 - 40 \mu\text{m}$ on the coordinate of the muon track in the bending plane and about 5 mm in the transverse plane.

3.2.6 The ATLAS data taking and the ATLAS trigger system

When the beams in the LHC reach the nominal energy and stable collisions are achieved, the detector sub-systems start collecting data.

For an instantaneous luminosity $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a proton-proton cross section of about $\sigma_{\text{inel}} = 85 \text{ mb}$ for inelastic processes that lead to the breaking up of the colliding protons and the production of high- p_T particles, the interaction rate is $R = L\sigma_{\text{inel}} = 8.5 \times 10^8 \text{ s}^{-1}$. At the nominal collision frequency of 40 MHz, collision take place every 25 ns. This means that in every bunch crossing there are about 21 collision events producing high- p_T particles. The exact number of collisions per bunch crossing will vary according to a Poisson distribution whose mean value depends on the bunch instantaneous intensity and focusing. Due to the length of the bunches, the longitudinal position of the collisions is spread around the nominal interaction point, according to a Gaussian distribution with a width of about 50 cm.

Given that the cross sections for the production of events that are relevant to the physics programme of ATLAS are much lower, typically only one out of these “minimum bias” events, and in only a fraction of all the bunch crossings, will produce the physical process under study. For instance, the production cross section of a Higgs boson in pp collisions as predicted by the Standard Model, for a Higgs boson mass of 125 GeV and at $\sqrt{s} = 14 \text{ TeV}$, is $\sigma_H = 63 \text{ pb}$. This leads to a Higgs boson production rate of 0.6 Hz, *i.e.* only one bunch crossing out of more than 600 millions will produce a Higgs boson. The other inelastic pp collisions in the same bunch crossing as the process of interest are called “pile-up” events and are typically soft QCD processes producing quarks and gluons that hadronise and produce “jets” of particles leading to signals in the tracking systems and in the calorimeters.

The “pile-up profiles” of the Run 1 and Run 2 data taking periods, *i.e.* the distributions of the average number μ of interactions per bunch crossing, are shown in Figure 3.8. The average value of μ was 9 in 2010–2011, 21 in 2012, 13 in 2015, 25 in 2016, and 38 in 2017 and 2018.

The very large collision rate and the large number of electronic channels to be read out and of information to be stored on disk for a collision event make it impossible to collect and save the signals from each sub-detector in every bunch crossing. A trigger system is thus active to rapidly identify which are the bunch crossings that most likely contain the small fraction of events are relevant to the ATLAS physics programme. Only for such events the full detector is read out and the information is stored on disk.

The ATLAS trigger system in Run 2 is a two-level system. Its goal is to reduce the event rate from the initial bunch crossing rate of 40 MHz down to about 1 kHz, which is the maximum rate at which full detector information can be extracted and recorded.

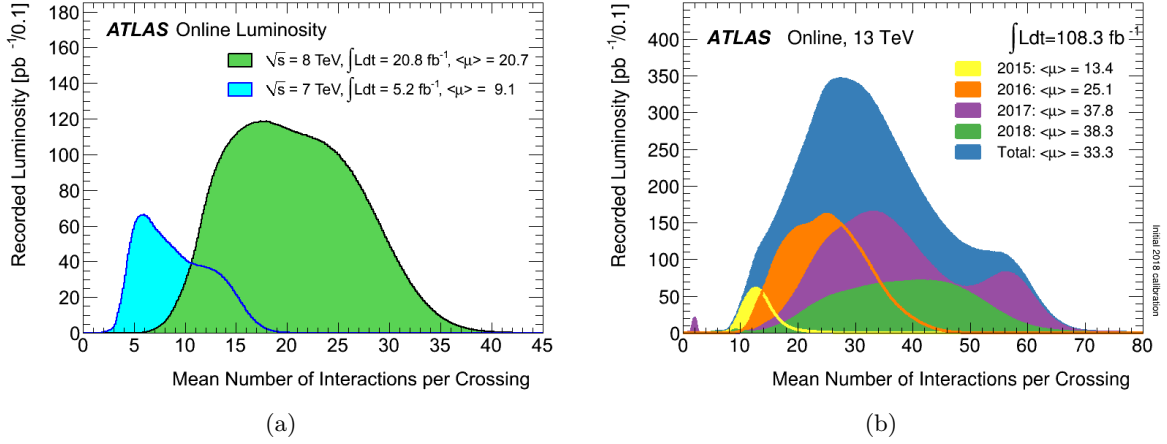


Figure 3.8 – Luminosity-weighted distribution of the mean number of interactions per proton bunch crossing for (a) Run 1 and (b) Run 2.

The Level-one trigger (L1) is a hardware trigger implemented in custom-built electronics. It processes coarse-granularity information from the calorimeters and the MS to reduce the event rate to about 100 kHz. It has an overall latency below $2.5 \mu\text{s}$. The L1 trigger searches for high transverse-momentum muon, electron, photon and jet candidates, or for events with large total energy or large imbalance in the total transverse momentum. For each event, the L1 trigger defines one or more Regions-of-Interest (RoI); these are the regions of the detector where the selection process has identified interesting features.

The High-Level Trigger (HLT) is a computer farm running offline-like software algorithms. It processes, within a nominal latency of 4 s, the information from all the ATLAS sub-detectors for events passing the L1 trigger, and decides whether an event should be kept for offline analysis or not. The HLT output rate is approximately 1 kHz. For the HLT decision only the detector sectors corresponding to the RoIs identified by the L1 trigger are read out, using the full detector granularity.

When temporary problems in one or more of the ATLAS sub-detectors or with the bending magnets appear, the trigger system might not be able to accept events from the LHC collisions, and the corresponding data would not be recorded. Dedicated crew of shifters and detector experts monitor constantly the status of each ATLAS sub-system to ensure that the data taking efficiency is as high as possible. The average data taking efficiency in ATLAS is around 93%.

Finally, to be usable for offline analysis, the data being recorded must be of good quality. Temporary problems like configuration issues with the data-taking settings of some detector, non-nominal high-voltage settings, and so on, would not stop data taking but would lead to data with poor quality. A team of “data quality” shifters and experts uses information from each sub-detector, based on low-level hardware information but also on comparison of high-level reconstruction performance with respect to some reference data-taking period, to declare which data “blocks” are useful for analysis. The fraction of data with good quality for analysis varies between 90% and 93% depending on the years, are shown in Figure 3.9.

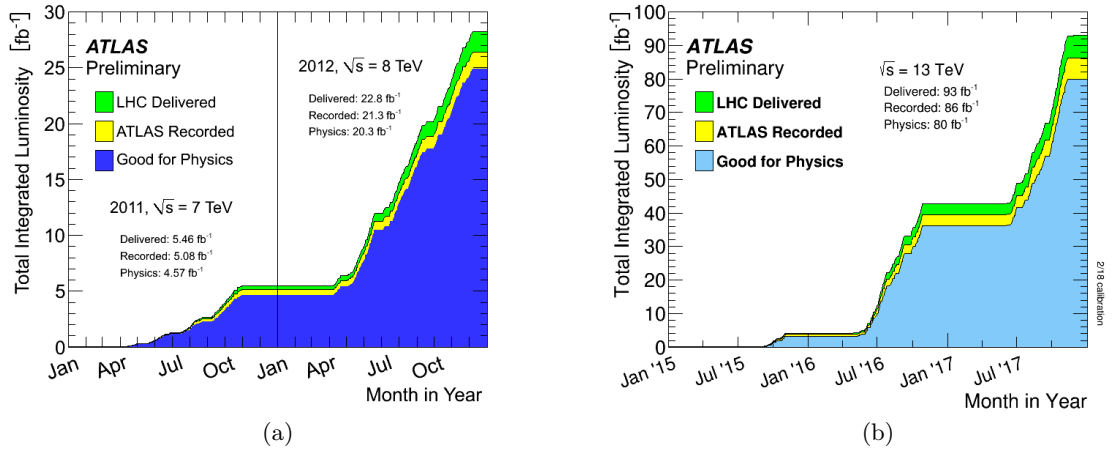


Figure 3.9 – Cumulative luminosity versus time delivered to (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams and for pp collisions in (a) Run 1 and (b) Run 2.

Chapter 4

Object Reconstruction and Performance

The reconstruction of the various particle trajectories and momenta combines the complementary information provided by the ATLAS sub-detectors, as illustrated in Figure 4.1. Charged tracks induce signals in the ID; electrons are then absorbed by the EM calorimeter, while charged hadrons are absorbed by the hadronic calorimeter, and muons pass through both calorimeters and leave signals in the MS. Neutral particles do not produce hits in the tracking devices (the ID nor the MS); photons either convert in the material upstream of the EM calorimeter to electron pairs, or are absorbed by the EM calorimeter itself; neutral hadrons deposit small amounts of energy in the EM calorimeter and are then absorbed by the hadronic calorimeter; neutrinos interact weakly with all the detectors and most likely escape the ATLAS detector without leaving any sign of their passage.

In the following the reconstruction of the different type of particles in ATLAS is described, as well as the main performance in terms of efficiency and/or resolution.

4.1 Charged particle track reconstruction

Charged-particle tracks are reconstructed from the signals that they induce in the ID [58, 59]. Due to the ID geometry, efficient track reconstruction is provided for $p_T > 0.5$ GeV and $|\eta| < 2.5$.

Two complementary track-finding algorithms start from space points in the silicon detectors and hits in the TRT and return estimates of the charged particle trajectories and momenta.

The default algorithm searches for track seeds in the pixel detector and then looks for SCT and TRT hits sufficiently close to the extrapolated track. Quality criteria on the track-hit association and on the minimum number of hits in the silicon detectors are applied, and a final refit of the track with the full information of all the three detectors is performed.

“Secondary” tracks from photon conversions or decays of long-lived particles might not produce enough hits in the pixel detector to form a track seed. The efficiency for such tracks is recovered by using a second, back-tracking, algorithm that searches for unused track segments in the TRT and then looks for hits in the silicon detectors that are sufficiently close to the extrapolation of the track towards the center of the detector. Again, a full refit of the track is performed combining the information from all the three detectors. If no hits in the silicon detectors are found by the back-tracking algorithm, a “TRT-only” track is formed.

Finally, the track collections from the two algorithms are combined into a single one after removing ambiguities and double counting.

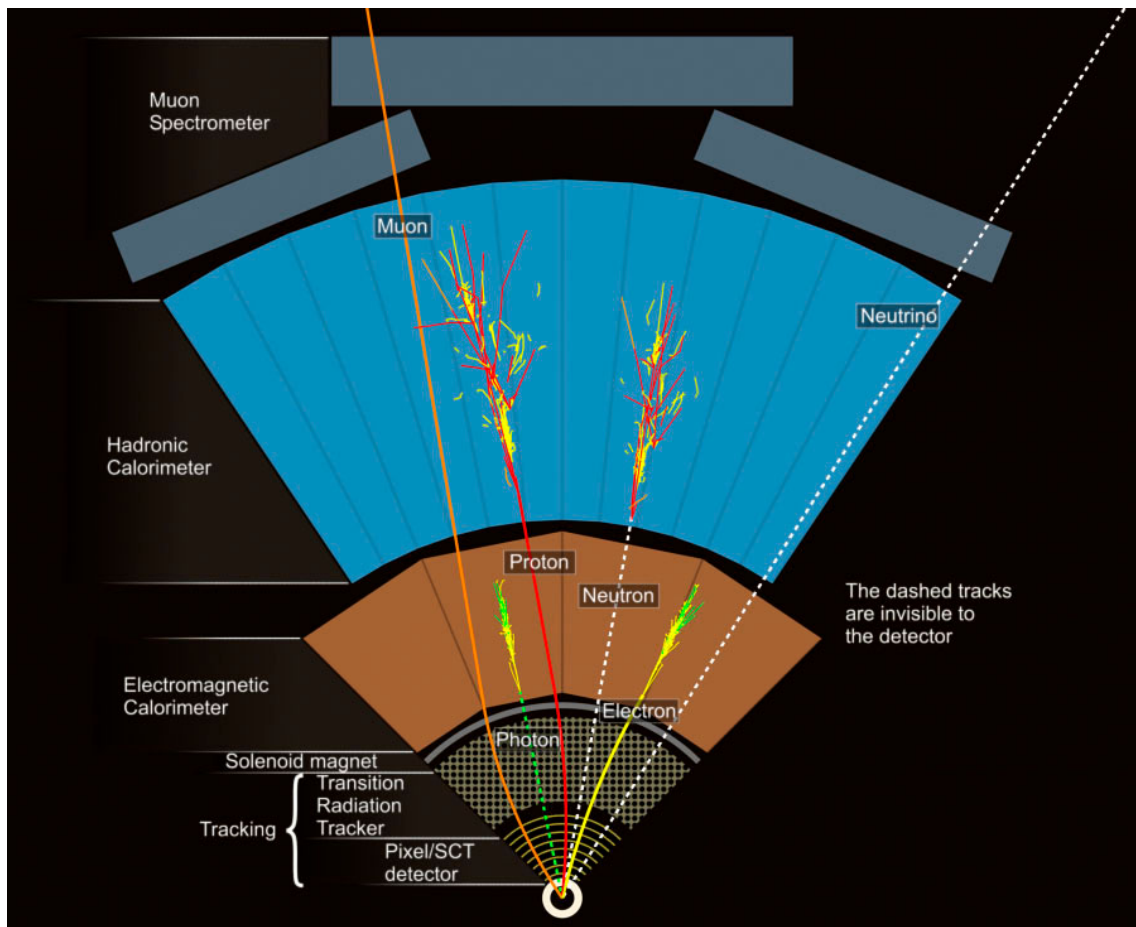


Figure 4.1 – Overview of the passage of some particles through the different sub-systems of the ATLAS detector. Dashed lines correspond to no detectable interactions with the detector material.

The tracking efficiency depends on the particle type, momentum and pseudorapidity, due to multiple scattering, bremsstrahlung (for electrons) and hadronic interactions with the material of the inner detector. The efficiency at $p_T = 5$ GeV is larger than 99% for muons, while for electrons it varies between 75% and 95%, and for pions it ranges between 80% and 95% as a function of $|\eta|$. The efficiency is independent of μ (mean number of interactions per crossing) within 1–2%.

The transverse momentum resolution achieved by the ID is

$$\frac{\sigma_{p_T}}{p_T} = \frac{0.05\% p_T}{\text{GeV}} \oplus 1\%; \quad (4.1)$$

The typical resolution for the track direction is

$$\sigma_\phi \approx 80 \mu\text{rad} \left(1 \oplus \frac{45 \text{ GeV}}{p_T} \right), \quad (4.2)$$

$$\sigma_{\cot\theta} \approx 1 \times 10^{-3} \left(1 \oplus \frac{7.5 \text{ GeV}}{p_T} \right). \quad (4.3)$$

In Run 1, the transverse impact parameter resolution for central tracks ($|\eta| < 0.2$) varies from 250 μm for $p_T = 400$ MeV to 20 μm for $p_T > 10$ GeV; the longitudinal impact parameter resolution for the same tracks and the same transverse momentum range varies from 410 μm to 120 μm .

In Run 2, the addition of the IBL, closer to the interaction point than the other ID modules, has led to an improvement in the z_0 resolution of about 2 (1.5) for tracks with p_T of 1 (100) GeV and to an improvement in the d_0 resolution of about a factor 2 (1) for tracks with p_T of 1 (> 10) GeV [60], as shown in Figure 4.2.

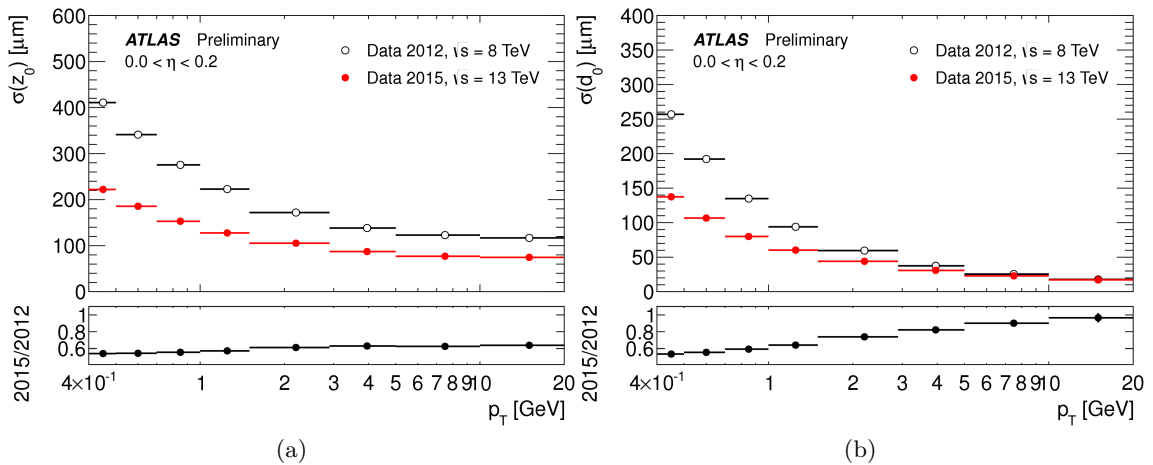


Figure 4.2 – (a) longitudinal and (b) transverse impact parameter resolution measured from data in 2015, $\sqrt{s} = 13$ TeV, with the Inner Detector including the IBL, as a function of p_T , for values of $0.0 < \eta < 0.2$, compared to that measured from data in 2012, $\sqrt{s} = 8$ TeV.

4.2 Primary vertex reconstruction

Primary vertices, *i.e.* the points where pp interactions take place in a bunch crossing, are reconstructed by looking for tracks with a common origin [61]. Only tracks with good quality, *i.e.* with no missing hit in the pixel detector and with a minimum number of hits in the silicon detectors, small transverse impact parameter ($|d_0| < 4$ mm), well measured impact parameters ($\sigma(d_0) < 5$ mm and $\sigma(z_0) < 10$ mm) and $p_T > 400$ MeV are used. These requirements are tighter than the standard ATLAS track selection criteria in order to maintain a low rate of fake tracks from a random combination of hits even at large pile-up values. The impact parameter requirements reduce the contamination due to tracks produced in secondary interactions.

A two-step procedure is performed: first, a vertex-finding algorithm groups together the tracks belonging to a common origin; then, a vertex-fitting stage reconstructs the actual vertex position and its covariance matrix.

All vertices with at least two associated tracks are considered as primary vertex candidates. The reconstruction efficiency of hard-scatter primary vertices that produce reconstructed tracks is larger than 99%.

In the case of a small number of tracks, the primary vertex transverse position resolution may exceed $100\ \mu\text{m}$. The application of the beam-spot constraint significantly improves the transverse position resolution. The final transverse position resolution is better than $20\ \mu\text{m}$ in all cases.

The resolution on the longitudinal (z) position of the primary vertices is determined by the intrinsic resolution of the tracks. It is about $30\ \mu\text{m}$ for events with a large number of reconstructed tracks (see Figure 4.3(a)).

Among the reconstructed primary vertices, the one with the highest sum of the squared transverse momenta of its tracks ($\sum p_T^2$) is considered as the hard-scatter primary vertex. This choice is motivated by the fact that the charged particles produced in hard-scatter pp collisions have on average a larger transverse momentum than those from pile-up interactions. The efficiency of such selection is shown in Figure 4.3(b). In simulated $t\bar{t}$ events, which produce a large number of tracks, this criterion has a selection efficiency – defined as the fraction of events in which the highest $\sum p_T^2$ vertex is closest to the simulated hard-scatter vertex – greater than 99% even for large pile-up. For simulated $Z \rightarrow \mu\mu$ events, with fewer number of tracks, the efficiency is still very high if both muons are in the acceptance of the ID, but decreases slightly with pile-up, reaching a value of 98% for $\mu = 40$.

4.3 Electron and photon reconstruction

Electron and photon reconstruction exploits information from the electromagnetic calorimeter, where the energy from electrons and photons is converted to an electromagnetic shower and partially turned into a ionisation signal of the liquid argon, and from the inner detector [62]. Electrons are expected to leave a track in the ID that, when extrapolated to the EM calorimeter, is close to a “cluster” of adjacent cells with significant energy, and with a good agreement between the momentum of the track measured by the ID and the energy of the EM shower detected by the calorimeter. Calorimeter cell clusters that are not matched to an ID track are considered as *unconverted* photon candidates, *i.e.* photons that did not convert to electron-positron pairs within the ID volume. Calorimeter cell cluster matched to two tracks originating from a common space point or to one track with the signature of an electron but without hits in the innermost pixel layer, are considered as *converted* photon candidates, *i.e.* photons that converted to e^+e^- pairs in the ID.

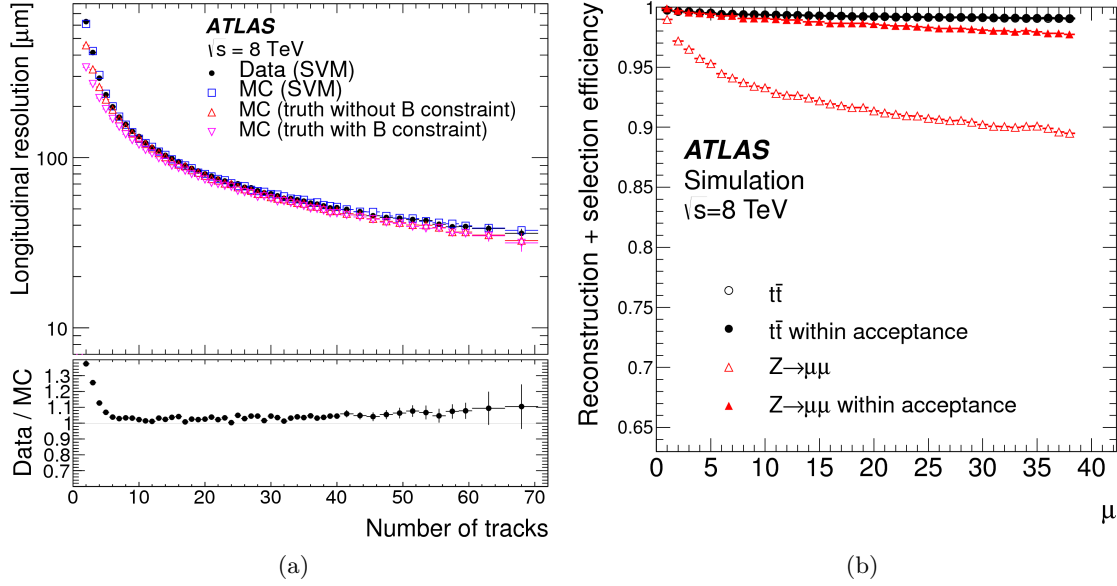


Figure 4.3 – (a) longitudinal position resolution of the reconstructed primary vertices as a function of the number of associated tracks. (b) efficiency as a function of the number of inelastic pp collisions per bunch crossing of the algorithm to identify the hard-scattering vertex by choosing the reconstructed primary vertex with largest $\sum p_T^2$ of the associated tracks.

The reconstruction algorithm proceeds in this order:

- it first selects clusters of calorimeter energy cells;
- it then considers the tracks in the inner detector, and
 - searches for conversion vertex candidates, *i.e.* track pairs with a common origin or single tracks with an electron signature and no hit in the innermost pixel layer;
 - searches for matches between the candidate clusters and the ID tracks or the conversion vertex candidates;
- builds the final “supercluster” of calorimeter cells, from which the energy and position is computed;
- finally, an ambiguity resolution removes the overlaps between candidates reconstructed both as an electron and as a photon.

The first step of the electron and photon reconstruction is the identification of three-dimensional topological clusters (also called *topo-clusters* in the following) of neighbouring cells with suffi-

cient energy [63]. The (EM and hadronic calorimeter) cells are grouped together in topo-clusters by a growing-volume algorithm based on the significance of their energy, defined as the ratio between the absolute value of the cell energy and the expected noise.

The reconstruction algorithm uses a “4-2-0” pattern:

- “seed cells”, *i.e.* cells with energy significance greater than four are searched for and used to define the initial *proto-clusters*;
- cells contiguous to the seed cluster with energy significance greater than two or zero are added to the proto-cluster;
- if a neighbouring cell has significance greater than two, then also its neighbours are included in the proto-cluster;
- if a neighbour is another seed cell with significance greater than four, the two proto-clusters are merged;
- if two proto-clusters share a cell with significance greater than two, they are merged.

This procedure is performed iteratively until a final set of neighbouring cells with energy significance between zero and two is added to the proto-cluster.

Finally, proto-clusters with two or more local maxima are split between the corresponding signal peaks. Local maxima are defined as cells of the second and third layer of the EM calorimeter or of the first layer of the forward calorimeter with energy above 500 MeV, at least four neighbours, and none of the neighbours has higher energy. The clusters obtained from the previous procedure and whose EM energy fraction, defined as the ratio between the energy deposited in the cells of the three layers of the EM calorimeter and the total cluster energy, is larger than 0.5, are considered as clusters having originated from electromagnetic showers. The hadronic calorimeter cells are then removed from such clusters. EM clusters with $E_T > 400$ MeV are the “seed clusters” retained for e/γ reconstruction.

The second step of the electron and photon reconstruction is the matching between tracks and the seed clusters. The ID tracks that are within regions of interest defined by the position of the seed clusters that pass loose requirements on the shower shape are refitted with a modified pattern reconstruction algorithm and using a Gaussian Sum Filter in order to allow for up to 30% energy loss at each material intersection and bremsstrahlung. The refitted tracks are then matched to the seed clusters, based on tight requirement on the distance between the track and the cluster barycenter in η and ϕ . If multiple tracks are matched to a cluster, the “best-quality” track is used to form an electron candidate. The quality of the track is based on the number of hits in the pixel detector, on the number of hits in the SCT, and on the ΔR distance between the track and the cluster barycenter.

The track-cluster matching step also takes care of identifying tracks from candidate photon conversions. The refitted tracks that have a high probability to be electron tracks as determined by the TRT are used. Pairs of tracks from a common space point and consistent with originating from a massless particle are considered as two-track conversion vertices. Tracks without hits in the innermost silicon layer are considered as single-track conversions. Conversion vertices are

then matched to clusters based on a ΔR geometric requirement. If multiple conversion vertices are matched to the same cluster, the “best-quality” vertex is chosen. The quality of the vertex is based on the number of reconstructed tracks (one or two), whether the tracks are reconstructed or not in the silicon detectors, and the radial position of the conversion vertex.

The third step of the electron and photon reconstruction is the building of the final cluster of cells belonging to the electron or photon candidates. The algorithm starts from the initial seed clusters, which are processed sequentially in descending E_T order, and tries to add “satellite” clusters to the seed cluster to form a so-called “supercluster”. Clusters that are added as satellites of higher- E_T seed clusters are removed from the initial list of seed clusters.

Electromagnetic clusters with $E_T > 1$ GeV matched to a track with at least four hits in the silicon tracker are considered as seed clusters for electrons. EM clusters with $E_T > 1.5$ GeV and no matched tracks or matched to a conversion vertex are considered as initial photon candidates. The e/γ reconstruction algorithm then adds to the seed cluster all “satellite” clusters with lower E_T inside a window $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ centered on the seed cluster barycentre. Such satellite clusters are usually originated by secondary EM showers from the same initial electron or photon.

For electrons, to recover hard bremsstrahlung, extra satellite clusters in a larger window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.3$ around the seed cluster barycenter are added to the supercluster if they are matched to at least one track and the best-matched track of the seed and satellite clusters is the same. For converted photons, to recover the cluster from the second track in case of asymmetric conversions, clusters are considered as satellites and added to the supercluster if they are either matched to a track from the conversion vertex associated to the seed cluster, or if they are matched to the same conversion vertex as the seed cluster.

The seed cluster reconstruction efficiency is expected from simulation to be close to 100% for electrons and photons in the EM calorimeter acceptance, excluding the barrel-endcap transition region ($1.37 < |\eta| < 1.52$), and having $p_T > 20$ GeV. The final reconstruction efficiency is around 98% due to the small inefficiency of track-cluster matching or the presence of fake tracks that induce migrations at reconstruction level between electrons and photons.

The cells of the supercluster are used to determine the cluster barycenter, direction and energy. For each layer of the EM calorimeter the η and ϕ positions are first calculated as the energy-weighted barycenters of the cluster cells in that layer, with some small corrections to account for some systematic biases due to the detector geometry. The cluster position and direction are then determined from the measurements in each layer. For electrons and converted photons, tracking information is also used to determine the direction of the reconstructed particle. For photons, once the hard-scatter primary vertex has been identified, the direction is recomputed using the reconstructed primary vertex position, assuming they are originated in the hard scattering.

The energy of electrons and photons is determined through a multivariate (MVA) technique. A regression boosted decision tree (BDT) is trained on simulated samples of electrons, converted photons, and unconverted photons to correct the uncalibrated energies of electron and photon candidates. The simulation is based on Geant4 and includes a detailed description of the detector geometry and material. The calibration algorithm exploits the correlation between the true energy and a set of input variables which include the raw energy measured in the various layers of the EM calorimeter, the cluster barycenter, the position of the cells, and tracking information in the case of converted photons.

In data, *in-situ* corrections determined using $Z \rightarrow ee$ decays are applied as a final step of the calibration procedure. A comparison of the di-electron invariant mass peak position in data and simulation, as a function of the electron pseudorapidity, is used to determine small

pseudorapidity-dependent calibration constants $\alpha(\eta)$, defined as $E_{\text{reco}} = E_{\text{true}}(1 + \alpha)$. Photons from $Z \rightarrow \ell\ell\gamma$ events and lower-energy electrons from $J/\psi \rightarrow ee$ decays are used to check the energy calibration of photons and the linearity of the calorimeter energy response. Other cross-checks of the energy calibration are obtained by comparing the electron energy measured by the calorimeter and the momentum of the electron track measured by the ID for electrons from $W \rightarrow e\nu$. The typical size of the energy scale correction factors is of 1–2%, with an uncertainty between 0.01% and 0.1%.

The photon energy resolution depends on the photon energy E (in GeV) as:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c. \quad (4.4)$$

The *sampling term* $a/\sqrt{E}$, arising from statistical fluctuations in the shower development and in the collection of the energy, is estimated from test-beam data and with $J/\psi \rightarrow ee$ decays in pp collisions. It is around $10\%/\sqrt{E}$ in the EM calorimeter barrel and $17\%/\sqrt{E}$ in the EM calorimeter end-cap. The *noise term* b/E , arising from electronic noise in the readout of the cells of the cluster and from pile-up contributions to the cell energy, is around $500 \text{ MeV}/E$ and is thus negligible for electrons and photons of several GeV. It is determined from dedicated pedestal runs (electronic noise) and from the root-mean-square (RMS) of the E_T distribution of random clusters as a function of the number of pile-up events in pp collisions (pile-up noise). The *constant term* c arises from detector non-uniformities and is the limiting factor to the energy resolution at high energy. The expected value of the constant term from test-beams performed before the installation of the ATLAS detector is 0.7%. The observed value, determined from a comparison between the widths, in data and in the simulation, of the di-electron invariant mass distribution in selected $Z \rightarrow ee$ candidate events, is slightly larger, varying between 0.7% and 2% for $|\eta| < 2.4$, with an uncertainty of 0.1%–0.2%. The simulation is thus corrected to reproduce the data, by smearing the energy of the reconstructed electrons and photons by an extra constant term corresponding to the difference in quadrature between the observed one and the expected one.

To discriminate between signal *prompt* photons, *i.e.* photons not from hadron decays, and background photons from hadronic jets, reconstructed photon candidates are required to satisfy a set of orthogonal requirements on the energy in the hadronic calorimeter cells along the photon direction and on the transverse shower profile measured with the first two layers of the EM calorimeter. Three working points with different efficiency and hadronic jet rejection are defined: *loose*, *medium* and *tight*. The loose and medium working points only exploit a subset of the information and apply loose cuts to maintain a very high efficiency even at low p_T and are used for triggering or to collect background photon-enriched control samples. As an example, the loose selection has a photon efficiency rising from 97% at 20 GeV to above 99% above 40 GeV for reconstructed prompt photons and a rejection factor of about 1000 for reconstructed background photons. The tight working point uses more shower shape variables and applies tighter requirements than the loose and medium working point. The efficiency increases from 45–60% at 10 GeV to 95–98% above 100 GeV. It has a nominal rejection factor of about 5000 for background photons with $p_T > 40 \text{ GeV}$. The photon identification efficiency of the tight working point is measured with three control samples: photons from radiative decays of the Z boson, $Z \rightarrow \ell\ell\gamma$; electrons from $Z \rightarrow ee$ decays, after correcting the electron shower shapes for the small expected differences between electrons and photons; an inclusive sample of high- p_T prompt photons in which the residual background is estimated with a matrix method and subtracted. An example is provided in Figure 4.4(a).

Prompt electrons are discriminated from background electrons by means of a likelihood-based selection. The inputs for the calculation of the likelihood are the longitudinal and transverse shower profiles in the EM calorimeter, the quality of the track reconstruction and of the track-cluster matching quality, and the transition radiation detected in the TRT. Four working points with different efficiency and rejection are defined: *very loose*, *loose*, *medium*, *tight*. The very loose working point is mainly provided to select control samples which are relatively enriched in fake electron candidates with respect to samples in which one of the tighter criteria has been selected. The efficiency of the loose, medium and tight working points is measured in data with a control sample of electrons from $Z \rightarrow ee$ decays using a tag-and-probe technique, as shown in Figure 4.4(b).

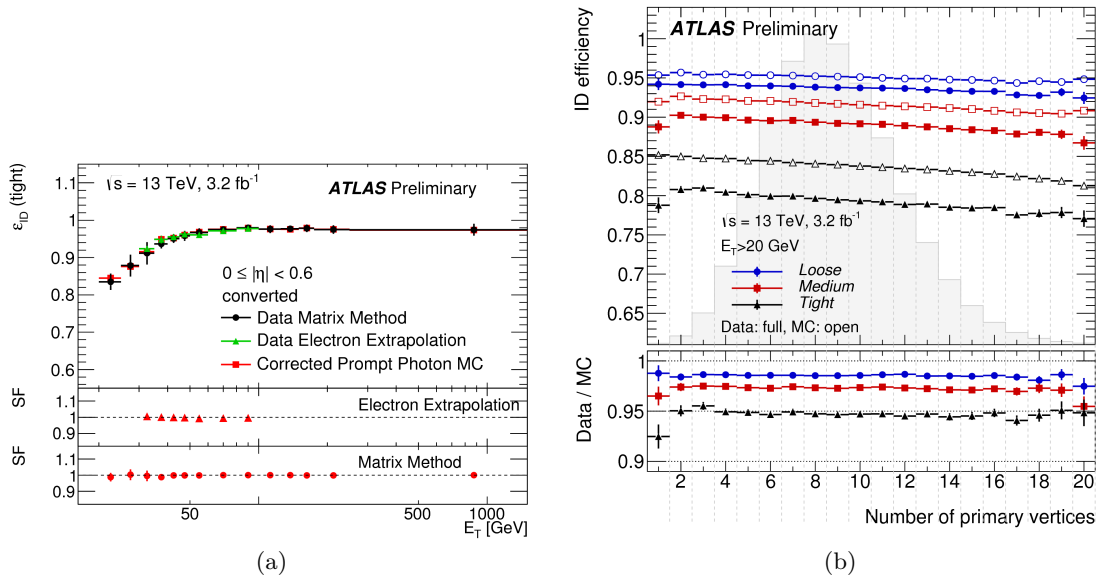


Figure 4.4 – The identification efficiency of (a) converted photons with $|\eta| < 0.6$ passing the tight working point [64], and (b) electrons, for various working points, [65].

Background electrons and photons from hadronic jets are further suppressed by requiring that there is low activity around the electron and photon direction in both the calorimeter and in the inner detector. A selection is applied on two quantities, the *calorimeter isolation* and the *track isolation* of the reconstructed candidates.

The calorimeter isolation, E_T^{iso} , is defined as the transverse energy deposited in the calorimeter cells in a cone of a certain radius ΔR (either fixed, typically between 0.2 and 0.4, or variable with the candidate p_T) around the e/γ direction. The contribution from the electron and photon itself is removed by excluding from the sum a rectangular core of cells (of size $5 \times 7 \eta \times \phi$ layer-2 cells) around the cluster barycenter. Leakage from the electron or photon outside the rectangular core is subtracted by applying a small correction (typically 2-5% depending on η) proportional to the candidate transverse momentum. Contribution from pile-up and underlying event is also estimated and subtracted by means of a jet area subtraction technique. The pile-up and underlying event energy density is evaluated as the median of the distribution of the transverse jet energies (see next section) divided by the jet area (in $\eta \times \phi$), using all jets (without any lower p_T threshold) reconstructed with anti- k_t algorithm [66] with a radius parameter of

0.5. The product of the area of the isolation cone times the pile-up and underlying event energy density is subtracted from E_T^{iso} .

The track isolation, p_T^{iso} , is defined as the scalar sum of the transverse momenta of the ID tracks with $p_T > 1$ GeV that are within a cone of a radius $\Delta R = 0.2$ around the e/γ direction. The electron track or the photon conversion tracks are excluded from the sum. Pile-up contribution is minimised by requiring the tracks to have small impact parameter with respect to the hard-scatter primary vertex.

4.4 Jet reconstruction

Due to color confinement, quarks and gluons hadronise immediately after their production, leading to the production of “sprays” of hadrons, called “jets”, with a direction more or less close to that of the initial parton. Such jets of hadrons interact with the material of the calorimeter, either through electromagnetic (for photons from e.g. $\pi^0 \rightarrow \gamma\gamma$ decays) or hadronic interactions. Typically all of the initial parton energy is absorbed by the calorimeter, and part of it is detected by its active, sampling regions.

Hadronic jets are reconstructed in the ATLAS detector by the anti- k_t algorithm [66] with a radius parameter of 0.4. The algorithm uses as inputs three-dimensional topological clusters of noise-suppressed calorimeter cells. The clusters are obtained by grouping together neighbouring cells that have significant energies compared to the expected noise.

The four momentum of a reconstructed jet is determined from the sum of the four momenta of the cells of its constituents, assuming that each one is massless [67]. The response of the calorimeter is calibrated using p_T and η dependent factors obtained from the simulation, to account for instrumental effects such as inactive material and non-compensation. A correction, dependent on the jet area, is also applied to subtract the additional energy from pile-up. Finally, an *in situ* jet energy scale (JES) correction is applied in data to account for residual differences between data and simulation. Such correction is determined from control samples of jets recoiling against well-calibrated particles (Figure 4.5). For central jets ($|\eta| < 0.8$) with $20 < p_T < 950$ GeV, well-balanced (in ϕ and p_T) Z +jet and γ +jet events are used, and the jet momentum is constrained by the well measured photon or Z boson energies. At higher p_T (up to few TeV) or in more forward pseudorapidity regions, multi-jet events in which the jet to calibrate recoils against a certain number of well-calibrated lower p_T , central jets are used.

Quality criteria are applied on the jet timing information and on the fraction of jet energy in the electromagnetic and hadronic calorimeters, as well as on the scalar sum of the transverse momenta of the ID tracks matched to the jet, to suppress fake jets from calorimeter noise, cosmic rays and beam-related backgrounds. In addition, a requirement on the “jet-vertex-fraction” (JVF) [68] is applied to suppress jets from hadrons produced in the “in-time” pile-up pp interactions overlaid with the pp collision of interest in the same bunch crossing. The JVF is defined as the sum of the scalar transverse momentum of the tracks that are associated with the jet and originated from the hard-scatter vertex, divided by the scalar p_T sum of all the tracks associated to the jet:

$$\text{JVF} = \frac{\sum_i p_T^{\text{trk}_i}(\text{PV}_0)}{\sum_j p_T^{\text{trk}_j}(\text{PV}_0) + \sum_{n \geq 1} \sum_j p_T^{\text{trk}_j}(\text{PV}_n)} \quad (4.5)$$

Here PV_0 is the chosen event primary vertex and PV_n , $n \geq 1$ are all the other primary vertex candidates from the pile-up interactions in the same bunch crossing. Further reduction of pile-up jets is obtained by using a selection based on a multivariate discriminant, called “jet-vertex-

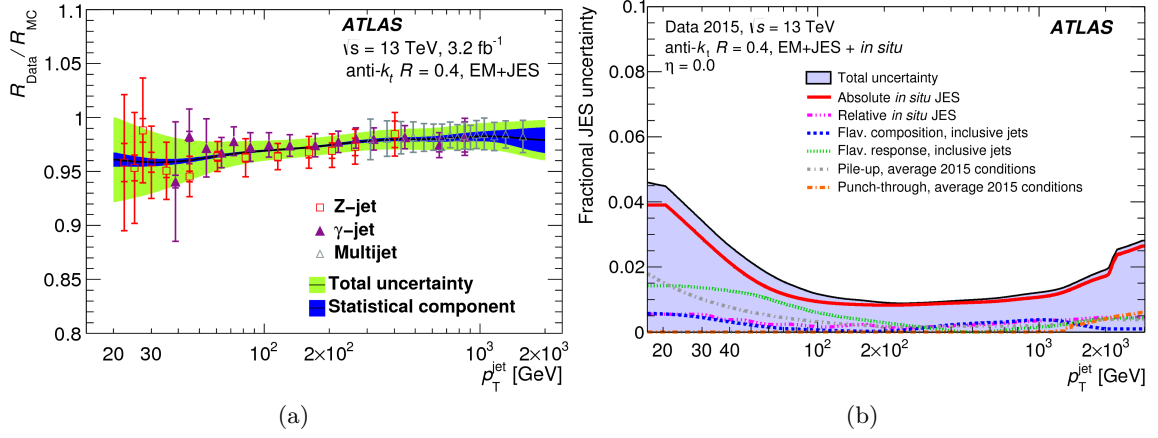


Figure 4.5 – (a) Ratio of the jet energy response in data to that in the nominal simulation as a function of jet p_T for Z+jet, γ +jet, and multijet in situ calibrations, using 2015 data. The final derived correction (black line) and its statistical (dark blue) and total (light green) uncertainty bands are also shown. (b) Combined uncertainty in the energy scale of fully calibrated jets as a function of jet p_T at $\eta = 0$.

tagger” (JVT), combining the information from JVF with the number N_{vtx} of reconstructed primary vertices. The typical performance of the JVF and JVT selections is illustrated in Figure 4.6.

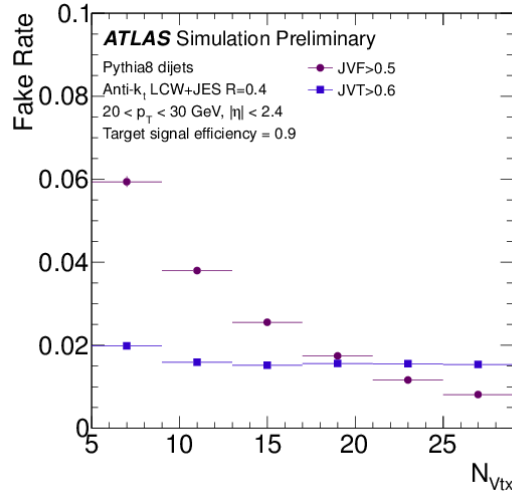


Figure 4.6 – N_{vtx} dependence of the pile-up jet fake rate when imposing cuts on JVT (blue) and JVF (violet) such that the inclusive hard-scatter jet efficiency is 90%.

4.5 Muon reconstruction

Muon tracks are reconstructed independently by the ID ($|\eta| < 2.5$) and the MS ($|\eta| < 2.7$, with a gap around $|\eta| < 0.1$). Muons also ionise the calorimeter active material, depositing there small amounts of energy that can be reconstructed. The information from the ID, the MS and the calorimeter are combined in order to maximise the efficiency, purity and momentum resolution of the reconstructed muons.

Four categories of reconstructed muon candidates are defined as follows:

- Combined (CB) muons have tracks reconstructed both by the ID and the MS, and a global refit of the track using the hits from both sub-detectors is performed.
- Segmented-tagged (ST) muons are ID tracks that, once extrapolated to the MS, can be matched to at least one local track segment in the MDT or CSC chambers.
- Calorimeter-tagged (CT) muons are tracks in the ID with $|\eta| < 0.1$ that can be matched to an energy deposit in the calorimeter compatible with that of a minimum-ionizing particle.
- Extrapolated (ME) muons are MS tracks outside the ID acceptance ($2.5 < |\eta| < 2.7$), whose impact parameters are loosely consistent with those of a track originating from the interaction point.

If multiple muon candidates are reconstructed from the same ID track, preference is given to CB candidates, then to ST ones, and finally to CT ones. Among ME muons sharing muon spectrometer hits, the candidate with the highest fit quality and number of hits is retained. To ensure a good reconstruction, a minimum number of hits in the ID and/or in the MS is requested.

Fake muon candidates arise from various sources: real muons from heavy flavour or pion/kaon semileptonic decays, or from cosmic rays; “punch-through” jets not fully contained in the calorimeters. Here “fake” muons mean that the reconstructed candidates do not originate from true, prompt muons produced in the primary pp collision. Muon candidates from cosmic rays are suppressed by requirements on their impact parameters with respect to the event primary vertex. Candidates from punch-through jets and decays of hadrons inside jets are suppressed by means of “isolation” criteria on the energy deposited in the calorimeter and on the p_T of the tracks in the ID near the muon track. Finally, muons from in-flight decays of (relatively) long-lived pions and kaons are characterised by trajectories with a “kink” in the pion or kaon decay point. The ID and MS parts of the track have thus significantly different directions and transverse momenta, and the combined track has a poor fit quality. A muon identification algorithm is based on such quantities. Four “working points” (“medium”, “loose”, “tight”, and “high- p_T ”) of such algorithm apply different selections on the input quantities and provide muon samples with different balance between efficiency and purity in order to satisfy the needs of measurements of processes with muons in the final state that are characterised by different signal-to-background ratios.

The muon efficiency and momentum scale and resolution is determined in data with control samples of Z , Υ and J/ψ decays to dimuons. The muon reconstruction efficiency is estimated

from events to be around 99%. The efficiency of the medium working point is shown in Figure 4.7(a). The muon momentum resolution σ_{p_T}/p_T grows from about 3% for $p_T = 20$ GeV to approximately 10% at 1 TeV. The muon momentum scale, determined from the position of the reconstructed $Z \rightarrow \mu\mu$ invariant mass peak (Figure 4.7(b)), is known to better than 0.1%.

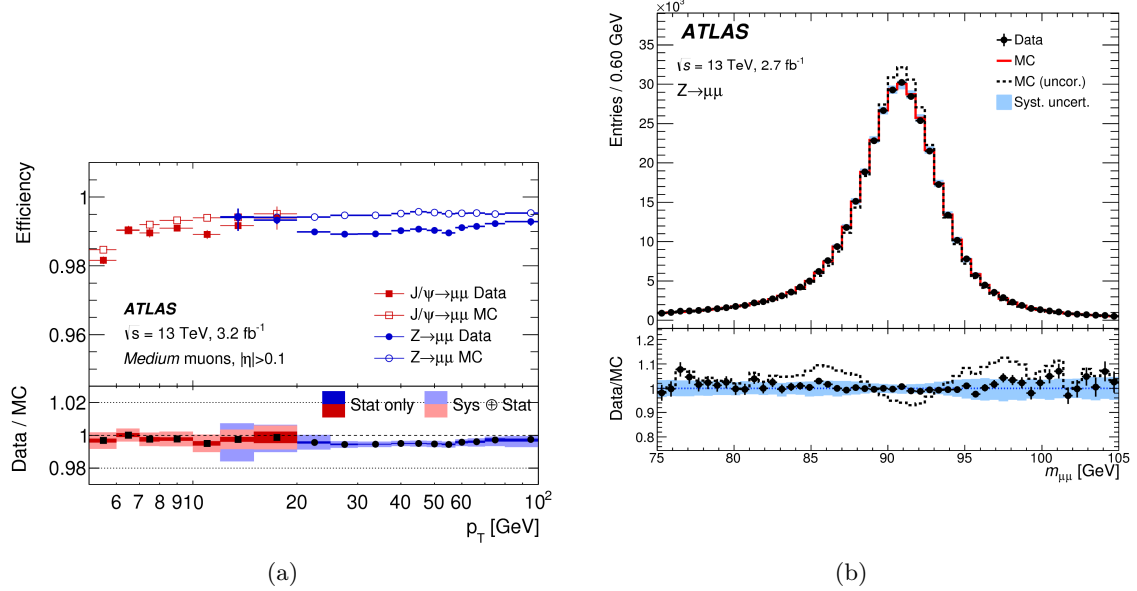


Figure 4.7 – Muon performance illustrative plots [69]. (a) Reconstruction efficiency for the Medium muon selection as a function of the p_T of the muon, in the region $0.1 < |\eta| < 2.5$ as obtained with $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events. The error bars on the efficiencies indicate the statistical uncertainty. The panel at the bottom shows the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties. (b) Dimuon invariant mass distribution of $Z \rightarrow \mu\mu$ candidate events reconstructed with CB muons. The upper panels show the invariant mass distribution for data and for the signal simulation plus the background estimate. The lower panels show the data to MC ratios.

4.6 Tau lepton reconstruction

Leptonically decaying τ -leptons are identified by means of the lighter charged leptons (electrons and photons) produced in their decay, as well as from the presence of neutrinos inducing transverse momentum imbalance (see next section).

Hadronically decaying τ -leptons are reconstructed from the interactions of their decay products with the calorimeter, using the anti- k_t jet algorithm also used for hadronic jets from quarks and gluons. They are reconstructed for $|\eta| < 2.5$, excluding the EM calorimeter barrel-endcap transition region ($1.37 < |\eta| < 1.52$), using all clusters of calorimeter cells within $\Delta R = 0.2$ of the jet axis [70]. Similarly to hadronic jets, events with τ -lepton candidates arising from calorimeter noise or beam-related background are rejected. The hadronically decaying τ lepton candidates are required to be matched to either one or three ID tracks, with a total net charge of ± 1 , corresponding to 1-prong and 3-prong decays. The energy of the reconstructed τ leptons is calibrated with a boosted regression tree.

Jets from quarks and gluons are discriminated from those induced by τ leptons by means of a boosted decision tree discriminant, exploiting the shape of the shower in the calorimeter and the properties of the ID tracks matched to the calorimeter clusters [70, 71]. Different working points are defined (*loose*, *medium*, *tight*) by applying different thresholds on the output of the BDT. The loose (medium) working point provides identification efficiencies of 60% (55%) for one-prong decays and 50% (40%) for three-prong decays (see Figure 4.8). Requirements on the electron likelihood of the τ track are applied to suppress electrons misidentified as one-track hadronic τ decays. The electron veto has an efficiency of around 95% for τ leptons, and an electron rejection factor between 30 and 150.

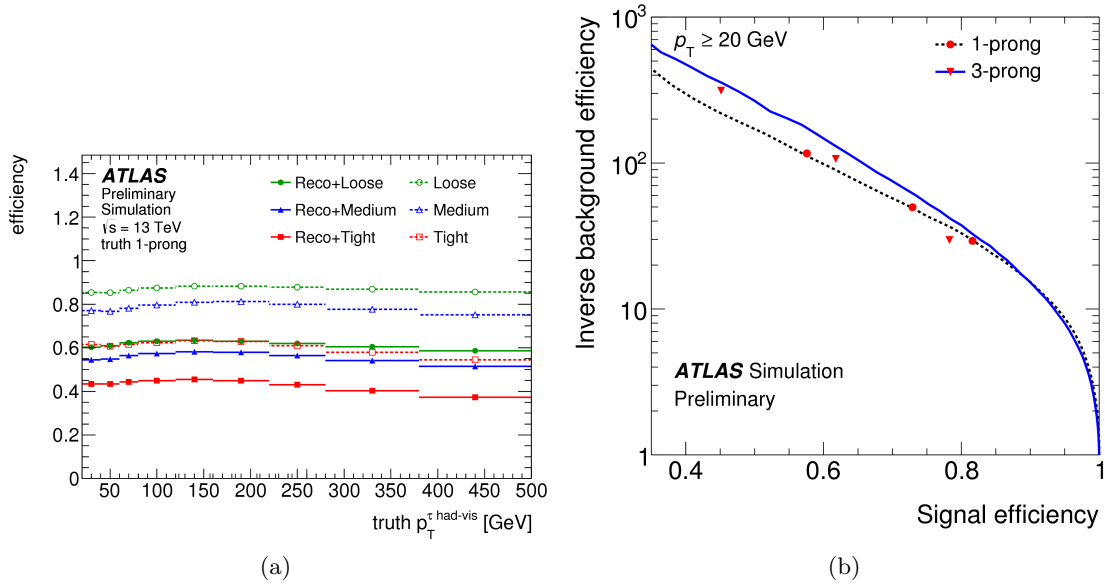


Figure 4.8 – Tau-lepton performance illustrative plots. (a) Efficiency for hadronic τ identification (open symbols) and combined reconstruction and identification efficiency (full symbols) as a function of the reconstructed p_T , for 1-track candidates. (b) Inverse of the efficiency for mistagging QCD jets as a function of the identification efficiency for hadronic τ candidates. The two lines refer to 1-track and 3-track candidates. The Loose, Medium and Tight working points are shown on these lines. The working points do not stay exactly on the line because this curve is derived for constant BDT threshold requirements, while the working points implement variable cuts to achieve a reduced p_T -dependence of the efficiency.

4.7 Missing transverse energy reconstruction

To identify the presence of final state particles that interact only weakly or do not interact with the detector, like neutrinos or long-lived particles of BSM theories, the principle of conservation of momentum is exploited. While along the z direction the fraction of momentum carried by the scattering partons is unknown, in the plane transverse to the beam direction the scattering partons have negligible momentum. Any transverse momentum imbalance of the reconstructed final state particles must therefore be due, aside from detector inefficiency or miscalibration, to the presence of such weakly interacting particles.

The transverse momentum imbalance is quantified by the *missing transverse energy* E_T^{miss} , which is the modulus of the transverse momentum vector, defined as the negative vector sum of the transverse momenta of the reconstructed particles [72]. The x , y components of the transverse momentum vector are thus calculated as:

$$E_{x,y}^{\text{miss}} = E_{x,y}^{\text{miss},e} + E_{x,y}^{\text{miss},\mu} + E_{x,y}^{\text{miss},\tau} + E_{x,y}^{\text{miss},\gamma} + E_{x,y}^{\text{miss},\text{jets}} + E_{x,y}^{\text{miss},\text{soft}}, \quad (4.6)$$

and E_T^{miss} is given by

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (4.7)$$

The electron, muon, tau-lepton, photon, and jet terms are determined from the negative vector sum of the transverse momenta of the corresponding calibrated candidates, with typical p_T thresholds between 10 and 25 GeV to ensure a good calibration. The *soft term* $E_{x,y}^{\text{miss},\text{soft}}$ accounts for low-momentum particles that have not been reconstructed as one of the previous object type, and is computed from the vector sum of the transverse momenta of all ID tracks with p_T above 400 MeV, $|\eta| < 2.5$, not matched to any of the objects used for the calculation of the other E_T^{miss} terms. To suppress contribution from pile-up, only tracks with small impact parameters with respect to the hard-scattering vertex candidate are used.

An additional variable used to quantify the transverse momentum imbalance is the track-based missing transverse momentum p_T^{miss} , which differs from E_T^{miss} only in the use of tracks in place of jets. The p_T^{miss} resolution is lower than that of E_T^{miss} since it is largely independent of pile-up, but its response is low as all neutral particles for $|\eta| < 2.5$ and all particles with $|\eta| > 2.5$ do not contribute to p_T^{miss} . A comparison of the resolution between E_T^{miss} , p_T^{miss} , and a missing transverse momentum variable $E_T^{\text{miss},\text{calo}}$ in which the soft term is based on unmatched energy deposits in the calorimeter rather than on tracks is shown in Figure 4.9.

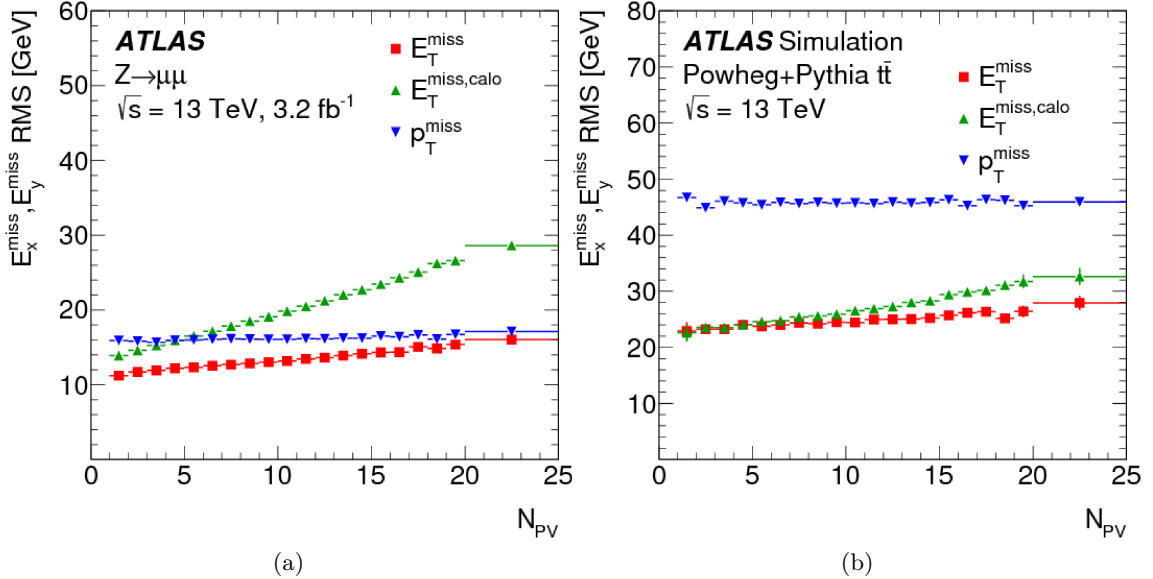


Figure 4.9 – Comparison of the E_T^{miss} , p_T^{miss} and $E_T^{\text{miss},\text{calo}}$ resolutions as a function of the pile-up activity measured in terms of the number of reconstructed primary vertices for (a) an inclusive $Z \rightarrow \mu\mu$ sample in data and (b) $t\bar{t}$ simulated events.

Chapter 5

b-jet identification in the ATLAS experiment: algorithms and performance

In this chapter, the algorithms used by the ATLAS experiment in the second period (2015–2018) of the LHC data taking (“Run2” in the following) to identify (“tag”) jets containing b hadrons are described. The method used to measure their performance for b -jets and its results are also described in detail; this was the subject of my service task to qualify as an ATLAS author.

The identification of jets containing b hadrons, with high efficiency, and with high rejection of jets containing c and light hadrons but not b hadrons, is a fundamental tool in precision measurements in the top quark sector and in searches of Higgs boson decays and new phenomena producing b quarks in the final state. To measure the production cross section of such processes, or to estimate accurately the normalisation of backgrounds from processes with similar kinematics but with charm and light quarks or gluons replacing b quarks in the final state, the efficiency of b -tagging a b -jet or a charm or light one needs to be determined with data control samples with the highest possible precision.

During the LHC Run2, ATLAS used two different releases of its reconstruction software, called **ATHENA**. Initially, **ATHENA** version 20.7 was used for the reconstruction and analysis of the data collected in 2015 and 2016. The publications based only on that partial subset of the Run2 data, like the one on the evidence of the Higgs boson decays to b -quark pairs described in the next chapter [23], are based on the 20.7 **ATHENA** release. In 2017, a new version (release 21) of the ATLAS reconstruction software was deployed. Data taken in 2017 and 2018 is reconstructed with this new release, which was also used to reprocess the data collected in 2015 and 2016, so as to have a uniform dataset. Such release of the reconstruction software was used for the recent publication on the observation of the Higgs boson decays to b -quark pairs also described in the next chapter [24].

In the following, the b -tagging algorithms used for the analysis of the ATLAS Run2 data, and the measurement *in situ* of the b -jet tagging efficiency (also called “efficiency calibration” in the following), are described. Section 5.1 summarises the algorithms used in **ATHENA** release 20.7, and their b -jet efficiency performance measured with 2015–2016 data, with an integrated luminosity of 36.1 fb^{-1} at a pp center-of-mass energy of 13 TeV, is given in section 5.2. Such results, which allowed me to qualify as an ATLAS author, have been recently published [22]. The results of the efficiency calibration of the algorithms used in **ATHENA** release 21 with 2015–

2017 data (about 80 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV), to which I also contributed, are not described here.

5.1 b -tagging algorithms in ATHENA release 20.7

The b -tagging algorithms used by ATLAS in ATHENA release 20.7 [73] are based on the charged particle tracks produced in the b quark decay and hadronisation and reconstructed in the inner detector, and exploit the long lifetime, high mass and decay multiplicity of b hadrons (see Figure 5.1).

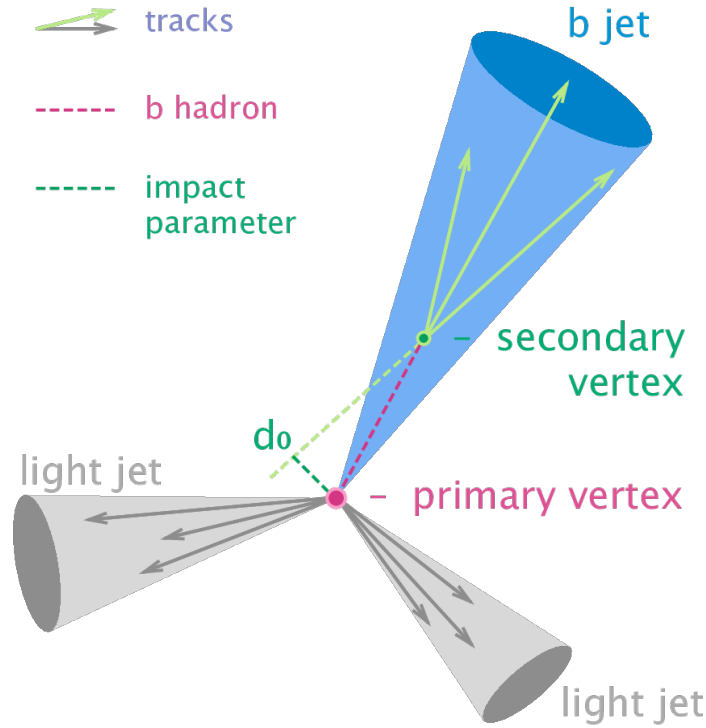


Figure 5.1 – Common principle of identification of jets initiated by b -hadron decays. The transverse impact parameter, d_0 , is the distance of closest approach of the track to the primary vertex point, in the r - ϕ projection. The tracks from b -hadron decay products tend to have large impact parameters which can be distinguished from tracks stemming from the primary vertex.

The tracks used in the b -tagging algorithms are associated to jets reconstructed in the calorimeter by using the angular separation ΔR between the track and the jet axis. The ΔR requirement is loose (large ΔR) for low jet p_T ($\Delta R = 0.45$ for 20 GeV) and tightens (smaller ΔR) at higher p_T (0.25 at 150 GeV). Further track selection depends on the specific algorithm as described below.

The lifetime (of the order of 1.5 ps) of b quarks implies that b hadrons with a transverse momentum of a few tens of GeV travel on average a few mm in the transverse plane before decaying, thus leading to topologies with at least one “secondary” vertex separated from the “primary” vertex where the primary proton–proton collision took place. Decay chains of the type $b \rightarrow c \rightarrow l$ (where l is a light quark) can even lead, due to the finite (but small) lifetime of c quarks, to topologies with a “tertiary” vertex from the charm quark decay. The tracks originating from

these secondary and tertiary vertices will have typically larger impact parameters, with respect to the primary vertex, than tracks from light and charm quarks or gluons produced directly in the hard collision taking place in the primary vertex. In addition, due to the relatively heavy mass (around 4 GeV) of the b quark, such tracks will have on average larger invariant mass and larger multiplicity than those from light quarks or gluons.

A few “low-level” b -tagging algorithms are exploited to discriminate, on a statistical basis, b -jets from charm and light ones. The output of these b -tagging algorithms are later combined in a multivariate discriminant to obtain the best separation between the different jet flavours. The three low-level b -tagging algorithms used in ATHENA release 20.7 are the following:

- **IP3D** is an impact parameter-based algorithm, derived as a likelihood-ratio algorithm based on the transverse and longitudinal impact parameter significance of the reconstructed track with respect to the selected primary vertex.

Tracks from the hadronisation of light quarks, with negligible lifetime, are expected to have impact parameters consistent with zero within their uncertainties (resolution). Tracks from the hadronisation of a b quark are expected to have impact parameters significantly different from zero. Additional discrimination is provided by the sign of the transverse impact parameter, d_0 . This exploits the fact that the decay point of the b hadron must lie along its flight path, as shown in Figure 5.1. The sign of a track’s d_0 is defined as positive if the track intersects the candidate b -jet axis beyond the primary vertex, and as negative if the intersection lies upstream of the primary vertex, where beyond and upstream are defined based on the jet direction. The jet axis coincides with jet direction; however, if an inclusive secondary vertex is found in the jet, the jet direction is replaced by the direction of the line joining the primary and the secondary vertices. The experimental resolution generates a random sign for the tracks originating from the primary vertex, while tracks from the b/c -hadron decay normally have a positive sign. Decays of e.g. K_s^0 and Λ^0 as well as interactions in the detector material also produce tracks with positively signed impact parameters, giving rise to a non-negligible probability of identifying light-flavour jets as b -quark jets.

IP3D is a powerful algorithm relying on both the transverse and longitudinal impact parameters, as well as on their correlations. It is based on a log-likelihood ratio (LLR) method in which for each track the measurement $S \equiv (d_0/\sigma_{d_0}, z_0/\sigma_{z_0})$ is compared to pre-determined two-dimensional probability density functions (PDFs) obtained from simulation for both the b - and light-flavour-jet hypotheses. The ratio of the b and light-jet probabilities p_b/p_u is defined as the track weight. The jet LLR weight is the sum of the logarithms of the individual track weights. The weights computed from the b/c probability ratios and c/l ones are also used. The LLR formalism allows track categories to be used by defining different dedicated PDFs for each of them. Two exclusive categories are used: the tracks that share a hit in the pixel detector or more than one hit in the silicon strip detector with another track, and those that do not. The track selection applied by IP3D is the following:

- track p_T above 1 GeV;
- $|d_0| < 1$ mm, $|z_0 \sin \theta| < 1.5$ mm;

- seven or more hits in the silicon detectors, with at most two missing hits where expected, at most one of which in the pixel detector.

Tracks consistent with the hypothesis of originating from photon conversions, Λ or K_S decays, or material interactions, as identified by the SV algorithm described later, are ignored.

- **SV** is a likelihood-ratio algorithm based on a few properties of the reconstructed inclusive secondary vertices within the jet. It tests all the track pairs in a jet for a two-track vertex hypothesis and removes vertices consistent with originating from conversions, Λ or K_S decays (based at the two-track invariant mass), or interactions with the detector material. Two-track vertices with invariant mass greater than 6 GeV are also removed as those are not likely to be from b or c hadron decays. If there is at least a two-track vertex remaining, a new vertex is fitted adding all the tracks from the other remaining two-track vertices that are compatible with (good χ^2 of the vertex fit) the vertex. The track selection applied by SV is the following:

- seven or more hits in the silicon detectors, with at most one hit shared with other tracks;
- χ^2 per degree of freedom of the track fit less than 3;
- tracks with $|d_0/\sigma_{d_0}| < 2$ and $|z_0/\sigma_{z_0}| > 6$ are removed as they most likely originate from pile-up interactions;

For the final vertex fit, at most 25 tracks are used. Since the average charged particle multiplicity from b -hadron decays is about 5, this selection is sufficiently inclusive to keep all reconstructed tracks, but avoids using the many tracks produced in the fragmentation of very energetic ($p_T > 300$ GeV) jets.

The properties of the secondary vertex used by SV to classify a jet as a b -jet or a charm or light one are the following:

- the invariant mass of the tracks forming the vertex, assuming they are pions;
- the fraction of charged jet energy in the secondary vertex;
- the number of tracks in the secondary vertex;
- the number of two-track vertex candidates used in the vertex fit;
- the distances, in the transverse plane and in space, between the primary and secondary vertices;

- the three-dimensional distance between the primary and secondary vertices, divided by its uncertainty;
 - the ΔR separation between the jet axis and the line connecting the primary and secondary vertices.
- **JetFitter** is an artificial neural network based on a larger set of properties of secondary and eventual tertiary vertices identified with a Kalman filter fit. The Kalman filter fit is used to find a common line passing through the primary vertex and the bottom and charm vertices (from a $b \rightarrow c \rightarrow X$ decay chain), approximating the b -hadron flight path. With this approach it is possible to resolve the b - and c -hadron decay vertices, if they are sufficiently separated with respect to the detector resolution, even in the case of a single track reconstructed from each one of the two vertices.

The quantities used as inputs for the JetFitter classification are the following:

- the number of 2-track vertex candidates before the decay chain fit;
- the invariant mass of the tracks from displaced vertices assuming they are pions;
- the significance of the average distance between the primary and the displaced vertices;
- the fraction of the charged jet energy in the secondary vertices;
- the number of displaced vertices with one track, or with more than one track;
- the number of tracks from displaced vertices with at least two tracks;
- the ΔR separation between the jet axis and the vectorial sum of the momenta of all the tracks from the displaced vertices

The same low-level algorithms were used in Run1. Their selection criteria and the way they are combined in a single multivariate discriminant were revisited prior to the start of the Run2 data taking in 2015. The reoptimisation of the b -tagging criteria was done to take into account two main changes that took place between Run1 and Run2:

- the installation of a fourth pixel layer (the IBL), at smaller radius than the three other pixel layers of the ATLAS inner detector. The position closer to the beam and the finer granularity along the z direction of the IBL significantly improve the impact parameter resolution of the reconstructed tracks with respect to Run1

- the track reconstruction algorithms were revisited to improve the treatment of pixel hits shared between multiple tracks inside high p_T jets, using a neural network pixel hit clustering.

The identification of jets originating from a b quark is performed by the MV2c10 algorithm [21]. It is a boosted decision tree (BDT) which uses as inputs the same input variables used by the low-level discriminants previously described (IP3D, SV, JetFitter), as well as the jet p_T and η , to exploit the correlations between the kinematic variables and the outputs of the low-level algorithms.

The MV2c10 BDT is trained on samples of b -jets and c - and light-jets in a simulated Monte Carlo (MC) sample of $t\bar{t}$ events in which at least one of the two W bosons from $t \rightarrow Wb$ decays hadronically. The MC sample is produced by generating events with the POWHEG program, interfaced with PYTHIA 6 [74] for the modelling of the parton shower, hadronisation and underlying event, to a GEANT4 [75] based detailed simulation of the ATLAS detector response [76]. In the training, jets reconstructed from the hadronisation of b quarks are treated as signal, while jets reconstructed from the hadronisation of c and light quarks (in a 7%:93% proportion) are treated as background; the b -jets p_T and η spectra are reweighted to match the corresponding spectra of the c - and light-jet mixture used as background. The true flavour of a reconstructed jet in the simulation is determined in the following way: if the cone of size $\Delta R = 0.3$ around the jet axis contains a b -hadron with $p_T > 5$ GeV, then the jet is labelled as a b -jet; otherwise, and if the cone contains a c -hadron with $p_T > 5$ GeV, the jet is considered a c -jet; otherwise the jet is a light (l) jet.

The output of the MV2c10 algorithm spans values from -1 to 1 , with b -flavour (light-flavour) jets yields values closer to 1 (-1). The expected MV2c10 output for b -, c - and light-flavoured calorimeter jets produced in $t\bar{t}$ events is shown in Figure 5.2(a), while Figure 5.2(b) shows the charm and light-jet rejection (*i.e* the inverse of the efficiency) as the function of the b -jet tagging efficiency.

Different selections on the MV2c10 discriminant correspond to different nominal efficiency (“working points”, WP, also called “operating points”, OP) for b jets produced in $t\bar{t}$ events. Operating points are defined by sets of selection criteria imposed upon the output of the b -tagging algorithm designed to provide a certain efficiency. Four operating points are used in ATLAS, corresponding to 60%, 70%, 77% and 85% b -jet tagging efficiencies in simulated $t\bar{t}$ events. The thresholds are different for calorimeter-jets and for track-jets. For each target efficiency there are actually two sets of operating points with the same average efficiency: a *single-cut* or a *flat-efficiency* operating point. The *single-cut* operating point corresponds to a constant requirement on the MV2c10 output, giving an efficiency that varies with jet p_T and η and that is equal to the target value only when averaged over the transverse momentum distribution of b -jets in simulated $t\bar{t}$ events. On the other hand, the *flat-efficiency* operating point applies different MV2c10 selections as a function of the jet p_T and η , ensuring a constant value of the efficiency as a function of these two kinematic variables. As an example, the charm and light-jet rejection as a function of jet p_T for the 70% single-cut and flat-efficiency OPs are shown in Figures 5.3(a) and (b).

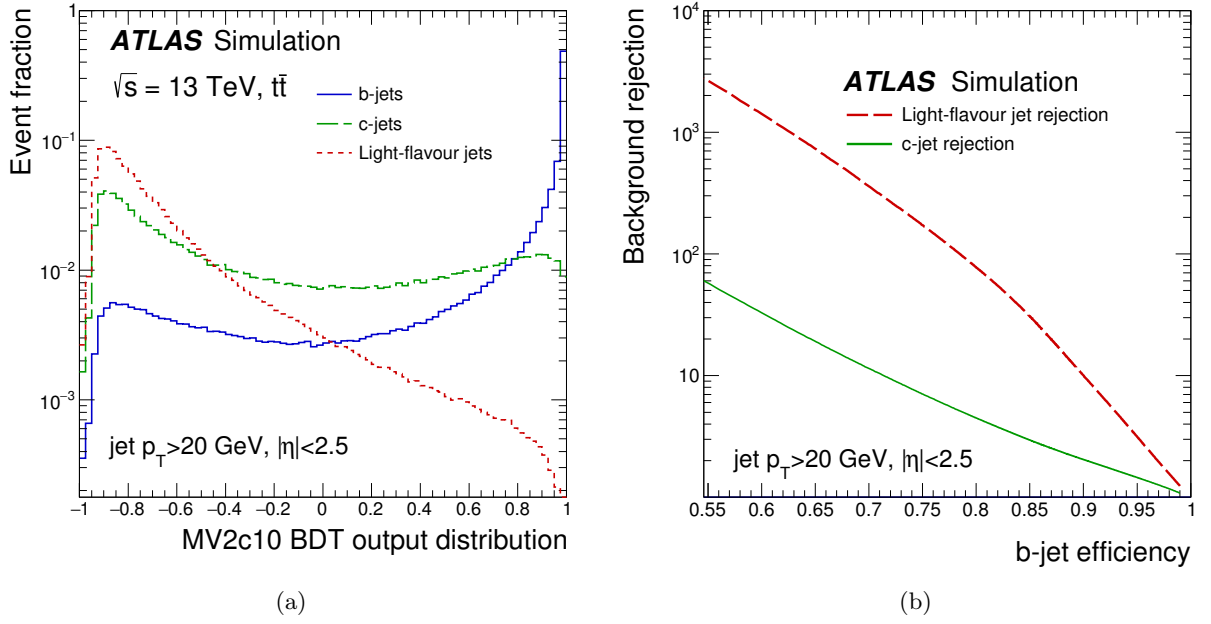


Figure 5.2 – (a) The MV2c10 output for b (solid line), c (dashed line) and light calorimeter jets (dotted line) in simulated $t\bar{t}$ events. (b) The light-flavour jet (dashed line) and c -jet rejection factors (solid line) as a function of the b -jet tagging efficiency of the MV2c10 b -tagging algorithm. The performance was evaluated on $t\bar{t}$ events simulated using POWHEG interfaced to PYTHIA 6.

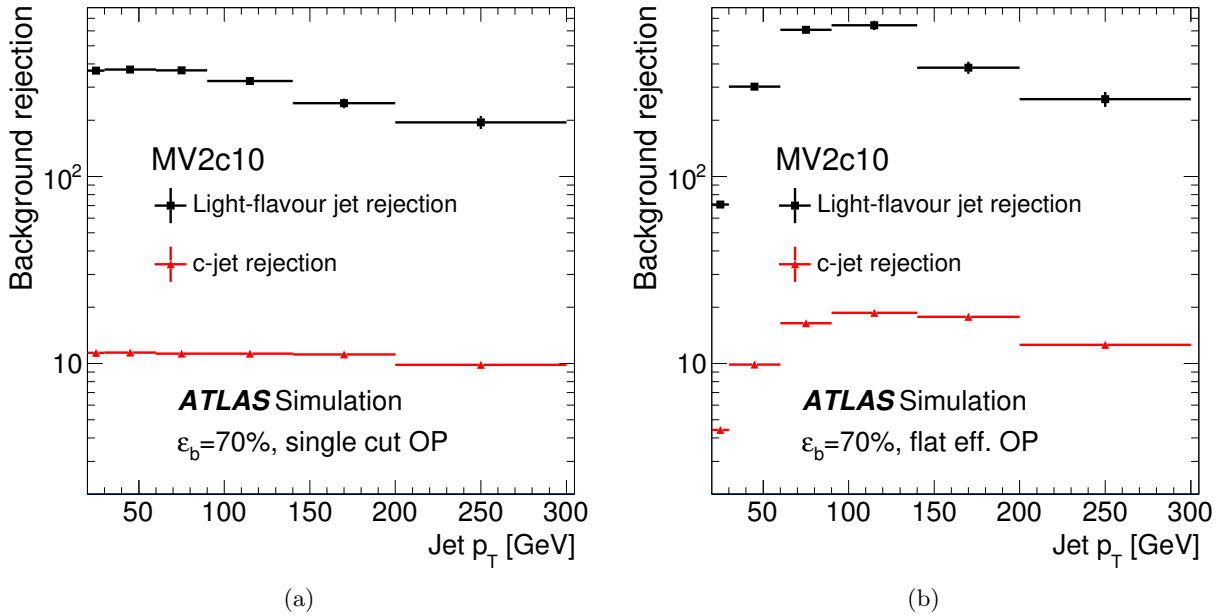


Figure 5.3 – The light-flavour calorimeter jet (squares) and c calorimeter jet rejection factors (triangles) at a b -tagging efficiency of 70% corresponding to (a) the single-cut OP and (b) the flat-efficiency OP as a function of the jet p_T for the MV2c10 b -tagging algorithms in $t\bar{t}$ events simulated using POWHEG interfaced to PYTHIA 6.

5.2 *b*-jet efficiency calibration with ATHENA release 20.7 and 2015–2016 data

A measurement of the efficiency of the *b*-tagging MV2c10 algorithm with 36.1 fb^{-1} of *pp* collisions at a centre of mass energy of 13 TeV collected by the ATLAS detector in 2015 and 2016 has been performed. The measurement has been performed for calorimeter-jets with $p_T > 20 \text{ GeV}$ and for track-jets with $p_T > 10 \text{ GeV}$; in both cases, the jet axes are required to be in the ID acceptance, $|\eta| < 2.5$. The measured efficiencies are then compared to the predictions of Monte Carlo (MC) simulations of *b*-jets produced in $t\bar{t}$ events, and data-to-MC efficiency scale factors are extracted, in order to correct the *b*-tagging efficiency of *b*-jets in all ATLAS simulated samples. The measurements have been performed for all the operating points and for both the single-cut and fixed-efficiency versions; in the following only the results for the most-used 70%, single-cut working point are shown.

The method works in this way:

- a sample of jet “probes” highly enriched in *b*-jets from $t\bar{t}$ events (due to the $t \rightarrow Wb$ branching fraction being close to 100%) is obtained with a certain selection which does not make any requirements on the *b*-tagging variables;
- the fraction of the probes that pass the *b*-tagging requirements is used to estimate the *b*-tagging efficiency;
- the effects due to background contamination from non- $t\bar{t}$ events and from light flavor jets in $t\bar{t}$ events are corrected for using MC simulations. Systematic uncertainties originating from uncertainty of the simulations are evaluated.

The “tag-and-probe” technique is used to select events consistent with the final state of the process $t\bar{t} \rightarrow WbWb \rightarrow e\nu b\mu\nu b$, by requiring the presence of an opposite-sign electron-muon pair, large missing transverse energy, and exactly two jets. At least one of the two jets is required to be *b*-tagged, and is (together with the leptons and the E_T^{miss}) the “tag”; the other jet is considered as a “probe” for the *b*-tagging efficiency measurement. If both jets in the event are *b*-tagged, they are both considered as probes. With these requirements, more than 90% of the selected candidates originate from $t\bar{t}$ events. The background comes from single top, *Z*+jets and di-boson processes, as well as from non-*b*-jets in $t\bar{t}$ events; their contributions are estimated with MC simulations. Requiring a dileptonic $t\bar{t}$ decay strongly reduces the number of non-*b* jets in the event, and thus combinatorial background, as well as the background from non- $t\bar{t}$ processes. Choosing different-flavour leptons further suppresses the background from *Z*+jet events.

5.2.1 Data and simulated event samples

The calibration is performed using $36.1 \pm 1.2 \text{ fb}^{-1}$ of *pp* collisions collected in 2015 and 2016 at a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$. Only good-quality data taken when all the subdetectors were fully functional are used.

To optimise the selection or to subtract contamination due to non-*b* jets or non- $t\bar{t}$ events in the selected probe jet sample, samples of simulated Monte Carlo events are used. All samples

are produced with some event generator and then passed through a detailed simulation of the ATLAS detector based on GEANT4.

Events from $t\bar{t}$ production are generated at next-to-leading-order (NLO) accuracy in QCD using the POWHEG-BOX v2 [77, 78, 79, 80] generator and the CT10 PDF set [81]. The generator, which only produces the kinematic distribution of the partons and leptons from the matrix element, is interfaced to PYTHIA 6.428 with the Perugia 2012 set [82] of tuned parameters (tune) to model the parton shower, fragmentation and the underlying event. The top quark mass is set to $m_t = 172.5$ GeV. Following previous ATLAS data-vs-simulation comparisons of the p_T spectrum of the $t\bar{t}$ system as a function of the h_{damp} parameter, which controls the p_T of the first additional emission beyond the Born configuration, h_{damp} is set equal to the value giving the best agreement, which is $h_{\text{damp}} = m_t$. To simulate only events with a non-negligible probability of passing the selection, one of the two W bosons from the $t \rightarrow Wb$ decay is forced to decay to leptons.

The dominant background source apart from combinatorial jets in $t\bar{t}$ events is single top-quark (or antiquark) production in association with a W boson, denoted here as Wt . A minor contribution to the selected candidates originates from Z +jets and diboson production. The event generators used to produce the nominal samples for all these processes, as well as the generators or the settings used to produce alternative samples needed to estimate the systematic uncertainties associated with the MC-based inputs to the measurement, are summarised in Table 5.1.

In all simulated samples, except those produced with SHERPA [92], the EVTGEN [93] program is used to model the decays of bottom and charm hadrons. To simulate the effect of pile-up, additional pp inelastic collisions generated with PYTHIA 8 [94] are overlaid on all simulated samples. All simulated samples are then passed through the ATLAS reconstruction software.

Weights typically close to one are applied to the generated events to account for differences between data and MC simulations in the trigger and offline selection efficiencies of leptons and jets as well as for differences between data and MC simulations in the distribution of the number of pile-up collisions. Simulated events are also corrected so that the lepton and jet energy scales and energy resolutions match those determined from data control samples at $\sqrt{s} = 13$ TeV.

5.2.2 Efficiency measurement method

The b -tagging efficiency for b -jet is measured as the fraction of probe jets in data before (N_{data}) that pass ($N_{\text{data}}^{\text{pass}}$) the b -tagging requirement. To take into account the presence of light and charm-jets in the selected probe samples and the contamination from non- $t\bar{t}$ events, two MC-based corrections are applied:

1. First, the number of probes from non- $t\bar{t}$ events predicted by the simulation is subtracted from the data probe yields, thus obtaining the so-called “uncorrected efficiency”:

$$\varepsilon_{\text{data}}^{\text{Uncorr}} = \frac{N_{\text{data}}^{\text{pass}} - N_{\text{non-}t\bar{t}}^{\text{pass}}}{N_{\text{data}} - N_{\text{non-}t\bar{t}}} \quad (5.1)$$

Here, $N_{\text{non-}t\bar{t}}^{\text{pass}}$ is the number of probe jets not from $t\bar{t}$ events which pass the b -tagging requirement, while $N_{\text{non-}t\bar{t}}$ is the total number of probe jets not from $t\bar{t}$ events. This efficiency is called “uncorrected” because it is slightly biased due to the small fraction of probe jets that arise from charm and light jets in $t\bar{t}$ events.

Table 5.1 – Summary of the Monte Carlo event generators used to generate various physics processes, together with their basic parameter settings and the corresponding order in QCD of the perturbative calculation of the cross-section (at $\sqrt{s} = 13$ TeV) used to normalise the samples.

Process	Matrix element generator	PDF Set, Tune	Hadronisation/ Fragmentation	Order in pQCD of Inclusive σ
Nominal Generators				
$t\bar{t}$	POWHEG-BOX v2	CT10, PERUGIA2012	PYTHIA 6.428	NNLO+NNLL [83]
Single top (Wt)	POWHEG-BOX v1	CT10, PERUGIA2012	PYTHIA 6.428	NNLO [84]
$Z + \text{jets}$	MG5_AMC@NLO 2.2.2 [85]	NNPDF23LO [86], A14 [87]	PYTHIA 8.186	NNLO [88]
Diboson	SHERPA 2.1.1	CT10	SHERPA 2.1.1	NLO
Alternative Generators				
$t\bar{t}$	POWHEG-BOX v2	CT10, PERUGIA2012 RADLo [89]	PYTHIA 6.428	NNLO+NNLL
$t\bar{t}$	POWHEG-BOX v2	CT10, PERUGIA2012 RADHi [89]	PYTHIA 6.428	NNLO+NNLL
$t\bar{t}$	POWHEG-BOX v2	CT10, UE-EE-5	HERWIG++ 2.7.1 [90]	NNLO+NNLL
$t\bar{t}$	MG5_AMC@NLO 2.2.2	CT10, UE-EE-5 [87]	HERWIG++ 2.7.1	NNLO+NNLL
Single top	POWHEG-BOX v1	CT10, PERUGIA2012 RADLo	PYTHIA 6.428	NNLO
Single top	POWHEG-BOX v1	CT10, PERUGIA2012 RADHi	PYTHIA 6.428	NNLO
Single top	POWHEG-BOX v1	CT10, UE-EE-5	HERWIG++ 2.7.1	NNLO
Single top	MG5_AMC@NLO 2.2.2	CT10, UE-EE-5 [87]	HERWIG++ 2.7.1	NNLO+NNLL
Single top	POWHEG-BOX v1	CT10, PERUGIA2012	PYTHIA 6.428	NNLO
$Z + \text{jets}$	POWHEG-BOX v2	CT10, AZNLO [91]	PYTHIA 8.186	NNLO

2. The effect of the presence of non- b jets from $t\bar{t}$ events in the selected probe samples is corrected for using a $t\bar{t}$ MC simulation. The correct b -tagging efficiency is denoted as $\varepsilon_{\text{data}}$ and is obtained from the relation:

$$\varepsilon_{\text{data}}^{\text{Uncorr}} = f_b^{t\bar{t} \text{ MC}} \times \varepsilon_{\text{data}} + \quad (5.2)$$

$$(1 - f_b^{t\bar{t} \text{ MC}}) \times \varepsilon_{\text{non-}b}^{t\bar{t} \text{ MC}} \quad (5.3)$$

Here $f_b^{t\bar{t} \text{ MC}}$ is the fraction of probe jets in the $t\bar{t}$ simulation that originate from a b quark, and $\varepsilon_{\text{non-}b}^{t\bar{t} \text{ MC}}$ is the b -tagging efficiency for non b -jets predicted by the $t\bar{t}$ simulation.

The b -tagging efficiency of b -jets in $t\bar{t}$ events in data, $\varepsilon_{\text{data}}$, is thus obtained by solving the previous equation:

$$\varepsilon_{\text{data}} = \frac{\varepsilon_{\text{data}}^{\text{Uncorr}} - (1 - f_b^{t\bar{t} \text{ MC}}) \times \varepsilon_{\text{non-}b}^{t\bar{t} \text{ MC}}}{f_b^{t\bar{t} \text{ MC}}} \quad (5.4)$$

The measurement is performed in bins of the jet kinematic quantities (p_T , η) on which the b -tagging performance may depend on.

5.2.3 Object selection

This section describes the selection criteria for the primary vertex, lepton and jet candidates used in this measurement.

Primary vertex: Primary vertex candidates (Section 4.2) should have at least three tracks with transverse momentum greater than 400 MeV. If more than one primary vertex candidate is present in the same event, the one with the highest $\sum p_T^2$ of the associated tracks is chosen as the primary vertex.

Leptons: Electrons (Section 4.3) and muons (Section 4.5) are required to have $|\eta| < 2.5$ and $p_T > 27$ GeV.

Electron candidates are required to be in the fiducial region of the EM calorimeter where there are three longitudinal layers ($|\eta| < 2.47$), and to pass the likelihood-based electron selector using the **medium** working point in 2015 data and the **tight** working point in 2016 data (for consistency with the electron trigger selection which was tighter in 2016 than in 2015). Electrons in the transition region between the barrel and endcap EM calorimeter ($1.37 < |\eta_{\text{cal}}| < 1.52$), which has large material upstream and is characterised by a poorer rejection of fake electron and a worse energy calibration, are removed.

Only muon candidates reconstructed from a combination of the tracks reconstructed by the inner detector and the muon spectrometer are used. The medium identification criteria are applied.

Both electron and muon candidates are required to have small impact parameters with respect to the primary vertex, $|d_0|/\sigma_{d_0} < 5$ or 3 for electrons and muons respectively, and $|z_0 \sin \theta| < 0.5$ mm for both electrons and muons.

Both electron and muon candidates are required to pass isolation criteria based on the energy deposited in the calorimeter and the tracks reconstructed in the ID in cones with axes centered on the lepton directions. The efficiency of the calorimeter (tracker) isolation requirement is 96% (99%) for leptons from Z boson decays.

Leptons with a lower p_T threshold ($p_T > 7$ GeV) passing looser identification criteria (loose working points of the electron and muon selectors) and isolation requirements are used to veto events with extra leptons, typically from di-boson production.

Calorimeter Jets: Calorimeter jets (Section 4.4), or simply jets if not specified otherwise, are required to have transverse momenta $p_T > 20$ GeV and to be within the acceptance of the inner detector, $|\eta| < 2.5$, where b -jet identification (which relies on the high spatial resolution of the inner detector) is possible. In order to reduce the contamination of jets arising from additional pile-up interactions, the jet-vertex tagger output of jets with $p_T < 60$ GeV and $|\eta| < 2.4$ is required to be greater than 0.59. Events with jet candidates highly likely to originate from non-collision backgrounds or from calorimeter noise are vetoed.

Track Jets: Track jets are reconstructed from inner detector tracks using the anti- k_t algorithm with distance parameter $R = 0.2$. The tracks are required to have $p_T > 0.5$ GeV, to have at least one hit in the pixel detector and six hits in the silicon strip detector, and to be matched to the hard scatter vertex requiring $|z_0 \sin(\theta)| < 3$ mm. Such thresholds greatly reduce the number of tracks from pile-up interactions whilst being highly efficient for tracks from the hard scatter vertex. Once the track jet axis is determined, a second step of track association is performed to select tracks with looser impact parameter requirements in order to collect the tracks needed for effectively running the b -tagging algorithms. Track jets with at least two tracks, $p_T > 10$ GeV and $|\eta| < 2.5$ are used for the analysis.

Jet Flavour: In the simulation, a jet flavour label is assigned using particle level information by matching jets to weakly decaying b and c hadrons with $p_T > 5$ GeV, in a cone of radius $\Delta R = 0.3$. The flavour labelling is exclusive, with the hadron matched only to the closest jet. If a b -hadron is found within the cone the jet is labelled as a b -jet. If no b -hadron is found, the search is repeated for c -hadrons, then for τ leptons. If no match is found for b -hadrons, c -hadrons or τ leptons, the jet is labelled as a light-flavour jet.

B-tagging: The working points that are calibrated in this study have nominal efficiencies of 60%, 70%, 77% and 85% on simulated $t\bar{t}$ samples.

Overlap Removal: Loose leptons and calorimeter-jets in the event are subject to an overlap removal procedure, to avoid double counting: electrons with shared tracks with muons are removed; jets are removed if they are within $\Delta R = 0.2$ of electrons, whereas those within $0.2 < \Delta R < 0.4$ are kept, and the electron removed instead; in case of jets that overlap within $\Delta R = 0.4$ of muons, those with only 1 or 2 associated tracks (with $p_T > 500$ MeV) are removed, while those with more than 2 associated tracks are kept, with the muon being discarded. Track jets with $p_T < 10$ GeV are not used as this sample is dominated by light jets and the rejection of these jets by the b -tagging algorithms is low. Furthermore, track-jets which overlap with either one of the two signal leptons within $\Delta R < 0.2$ are removed.

5.2.4 Event and probe jet selection

Events were recorded using single-lepton triggers with lower p_T thresholds and looser identification and isolation criteria than those applied in the offline analysis. The trigger p_T threshold was 24 GeV for electrons and 20 GeV for muons in 2015, and 26 GeV for both lepton hypotheses in 2016.

The following event-level selection is applied to the reconstructed candidates:

- exactly one electron and one muon, passing the object selection criteria described in Section 5.2.3;
- the electron and the muon are required to have opposite charges;
- events with extra loose leptons are vetoed;
- the number of jets in the collection being calibrated (either $R = 0.2$ track-jets or $R = 0.4$ calorimeter-jets) is required to be exactly two after the overlap removal procedure;
- at least one of the two selected jets must b -tagged by the MV2c10 algorithm at the 85% working point (single-cut efficiency). This jet is called a “tag” jet.

If the event contains exactly one “tag” jet, the other jet is considered as a “probe” jet. If the event contains two tag jets, both jets are also considered as probes.

An alternative selection, in which the lepton charges are requested to have same sign (SS) instead of opposite sign (OS), is used to provide a control region for the estimation of the small contribution of events with non-prompt (fake) leptons, N_{Fake} , in which at least one lepton is non-prompt (i.e. it originates from a b or c hadron decay, a photon conversion, or misidentification of a hadron). The number of fake-lepton background events after the nominal selection is then assumed to be the same as the number of events in this SS control region, since the charge of fake leptons can be positive or negative with similar probability:

$$N_{\text{Fake}} = N_{\text{Data}}^{\text{SS}} \quad (5.5)$$

When comparing the data to the simulation in the following figures and tables, the fake-lepton component (in green) is obtained as described. To avoid double counting of the fake-lepton component, since part of the fake-lepton background is also included in the simulated MC samples, simulated events that are identified as fake-leptons based on MC truth information are removed from the other processes.

The yields in data and in the simulation are shown in Table 5.2. One can see that the dominant processes that contribute to the selected sample are $t\bar{t}$ and, to a lesser extent (5–8% of $t\bar{t}$), single-top production. Di-boson production and Drell-Yan events only account, according to the simulation, for 0.5–1.5% of the total number of selected events. The simulation predict a yield which is slightly higher than the data, but the differences are covered by the integrated luminosity uncertainty (3.2% relative) as well as by the modelling and experimental uncertainties on the simulated backgrounds.

A few comparisons between data and simulation for events passing the selection for the calorimeter-jet or track-jet calibrations are shown in Figure 5.4. A comparison between the distribution of some probe kinematic and tagging quantities in data and simulation for the selected probe jets is shown in Figure 5.5. The agreement between data and simulation is quite good for the kinematic variable distributions, while a certain disagreement is observed at the low value MV2c10 (dominated by light jets), which makes it very important to measure with data-driven techniques the efficiency of the MV2c10 tagger and to extract data/MC scale factors.

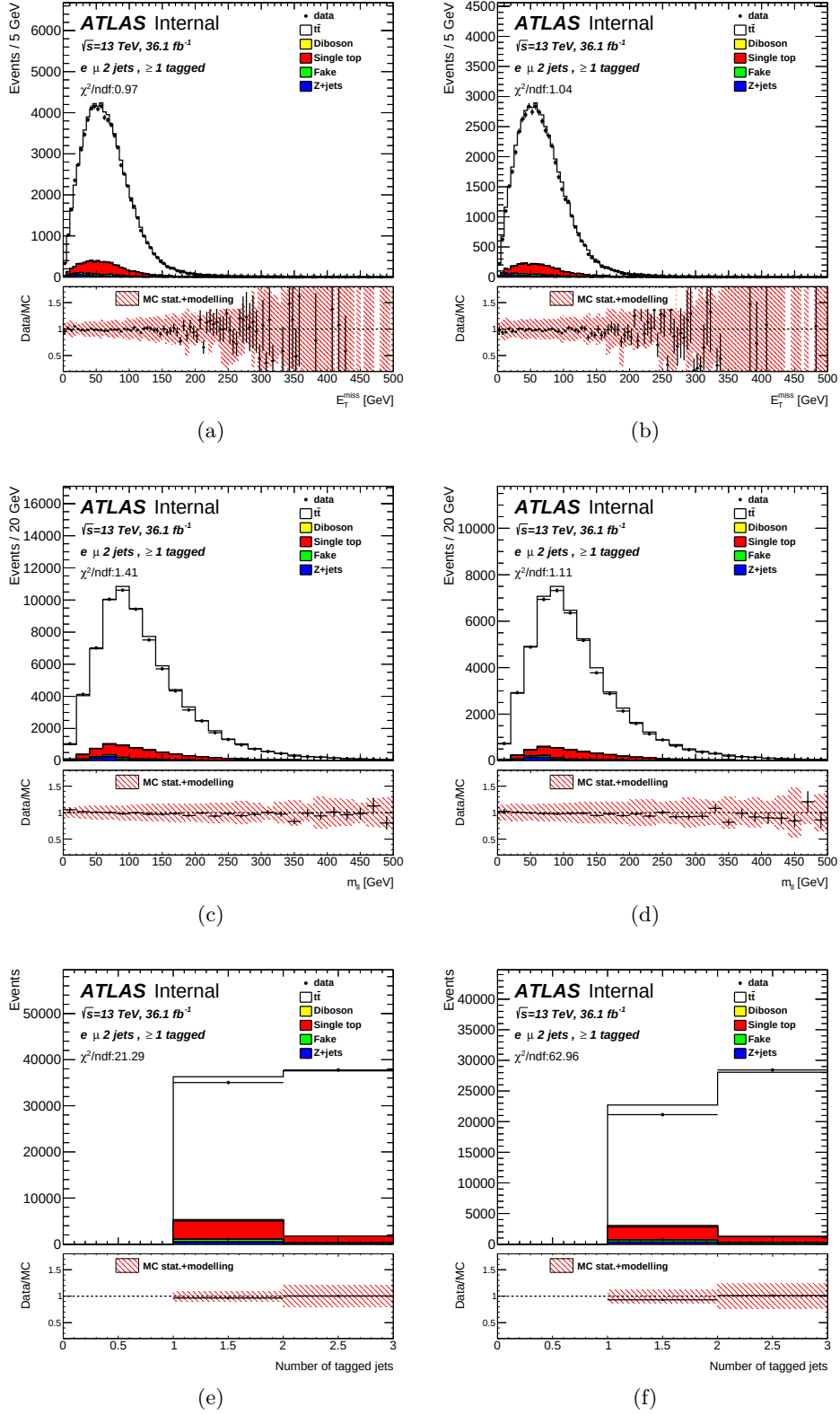


Figure 5.4 – Comparison of data and MC simulation for calorimeter-jets (left) and track-jets (right) after the event selection: E_T^{miss} (top), m_l (middle) and multiplicity of the tag jets (bottom). The contributions from the different processes are shown separately. The error band includes the MC statistical uncertainty and the modelling ($t\bar{t}$ single top and Z+jets) systematics uncertainty.

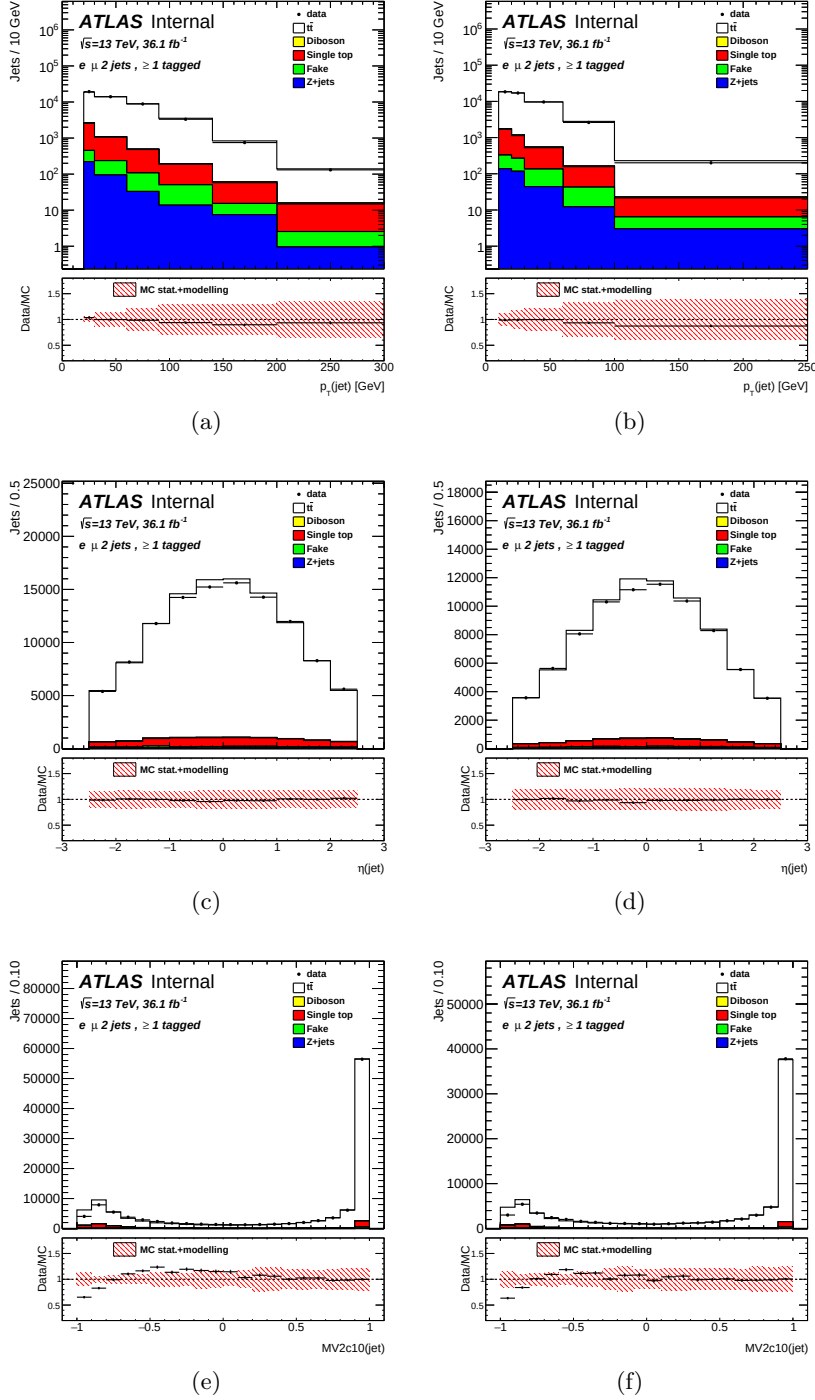


Figure 5.5 – Data/MC comparison of the probe jet p_T (top), η (middle) and MV2c10 (bottom), for calorimeter-jets (left) and track-jets (right). In the simulation the contributions from the different truth-flavoured jets (bottom, charm, or light ones) are shown separately. All simulated processes ($t\bar{t}$, single-top, diboson and Z +jets) are included. In addition, the fake-lepton component, estimated with data-driven techniques, is also shown. The error band includes the MC statistical uncertainty and the modelling ($t\bar{t}$, single top and Z +jets) systematics uncertainty.

Table 5.2 – The number of events and the statistical uncertainty, in 36.1 fb^{-1} of pp collisions, after the tag-and-probe selection for calorimeter-jets and track-jets calibration, as predicted by the simulation and as observed in data. The “fake leptons” is estimated using a data-driven method described in the text.

	calorimeter-jets	track-jets
diboson	291 ± 9	201 ± 7
singletop	5331 ± 39	3078 ± 30
Z+jets	570 ± 44	369 ± 36
$t\bar{t}$	66807 ± 157	46556 ± 132
fake leptons	853 ± 29	567 ± 24
total MC	73853 ± 170	50770 ± 142
data	72792	49566

5.2.5 Multivariate event discriminant

To further improve the b -jet purity of the selected sample, a multivariate classifier is applied to distinguish $b\bar{b}$ jet pair candidates produced in $t\bar{t}$ events from other type of jet pairs. The classifier is a boosted decision tree (BDT) and is trained, using the TMVA package [95], on simulated $t\bar{t}$ and single-top events (neglecting for simplicity the very small contribution from Z+jet and di-boson events), using as signal $b\bar{b}$ pairs in $t\bar{t}$ events and as background all non- $b\bar{b}$ jet pairs selected in $t\bar{t}$ and single top events. The training is performed separately for the calibration of calorimeter jets and of track jets. Seven kinematic variables, summarised in Table 5.3, derived from the jets and leptons momenta, the missing transverse momentum and the number of forward jets in the event are used as input variables to the BDT. The BDT output is called “Purity BDT” or $\mathcal{D}_{bb}^{\text{T\&P}}$ in the following.

Table 5.3 – Variables used in the *Purity* BDT to separate $b\bar{b}$ jets in $t\bar{t}$ events from other types of jet pairs.

Variable	Meaning
$p_T^{j_0}$	p_T of the leading- p_T jet
$p_T^{j_1}$	p_T of the subleading- p_T jet
$p_T^{l_0}$	p_T of the leading- p_T lepton
E_T^{miss}	Missing transverse momentum
nFjets	Number of forward jets
$\text{minR}(l_{0,j})$	Minimal ΔR separation between the leading lepton to all jets
m_{lj}	Minimum of the two averages of invariant masses of a jet and a lepton for the two combinations, symbolically, $\min((m_{l_0j_0} + m_{l_1j_1})/2, (m_{l_0j_1} + m_{l_1j_0})/2)$

The data/MC comparison plots for the input variables of the *Purity* BDT are shown in Figure 5.6 and Figure 5.7 respectively. Data and simulation agree well within the data statistical and MC mismodelling uncertainties.

The comparisons between the simulated signal and background distributions of the training variables are shown in Figure 5.8 and Figure 5.9 for the calorimeter-jets and track-jets calibration, respectively. The figures also show the distributions of a few other variables that were initially considered but were not used because did not provide additional separation between

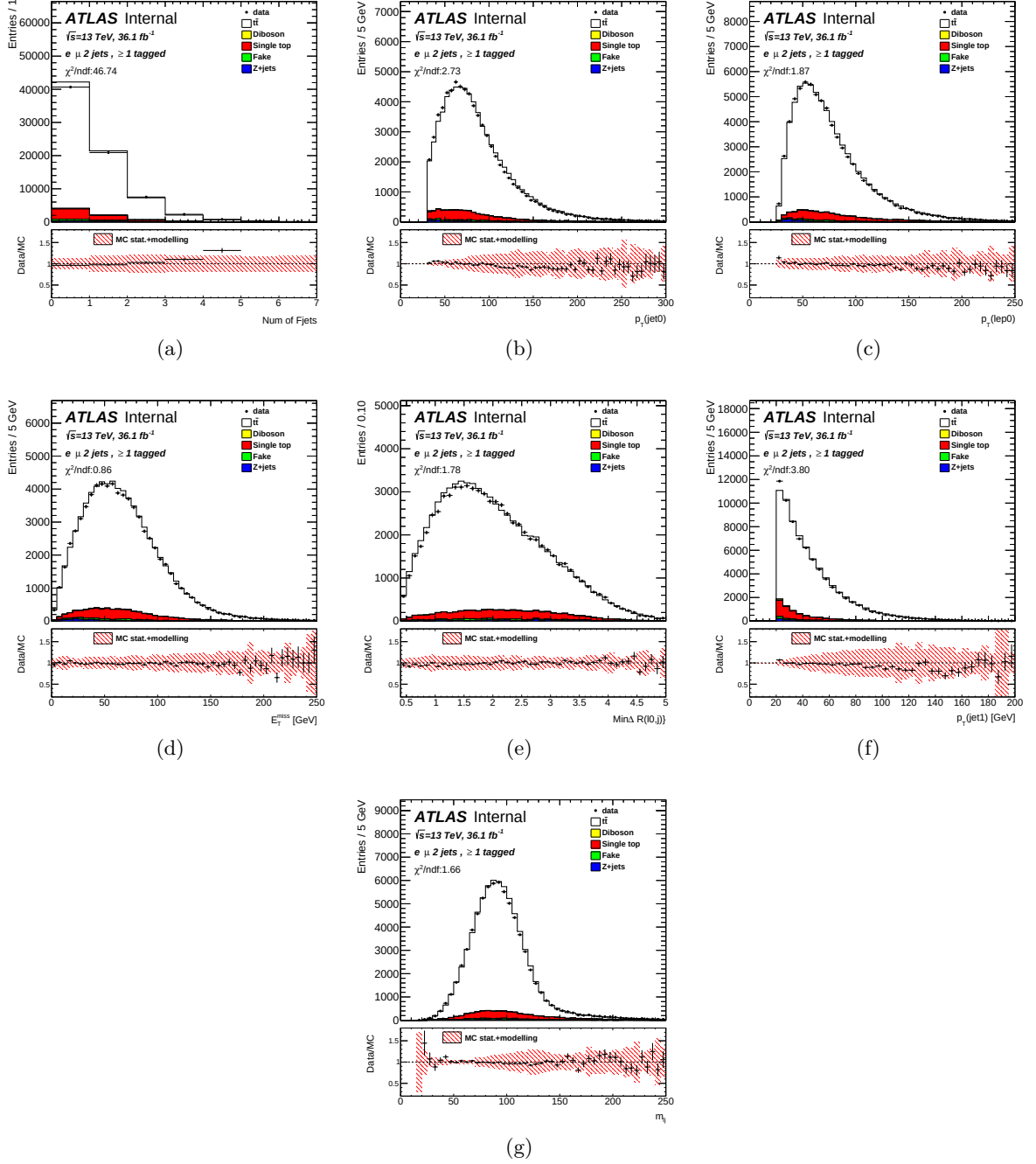


Figure 5.6 – Data/MC comparison of the distributions of the input variables of the *Purity* BDT, in the calibration of calorimeter jets, after having applied the tag-and-probe selection described in Sec. 5.2.4. From top to bottom, left to right: number of forward jets, p_T of the leading jet, p_T of the leading lepton, missing transverse energy, minimum ΔR separation between the leading lepton and all jets, p_T of the trailing jet, and lepton-jet invariant mass m_{lj} . The error band includes the MC statistical uncertainty and the modelling ($t\bar{t}$, single top and Z +jets) systematics uncertainty.

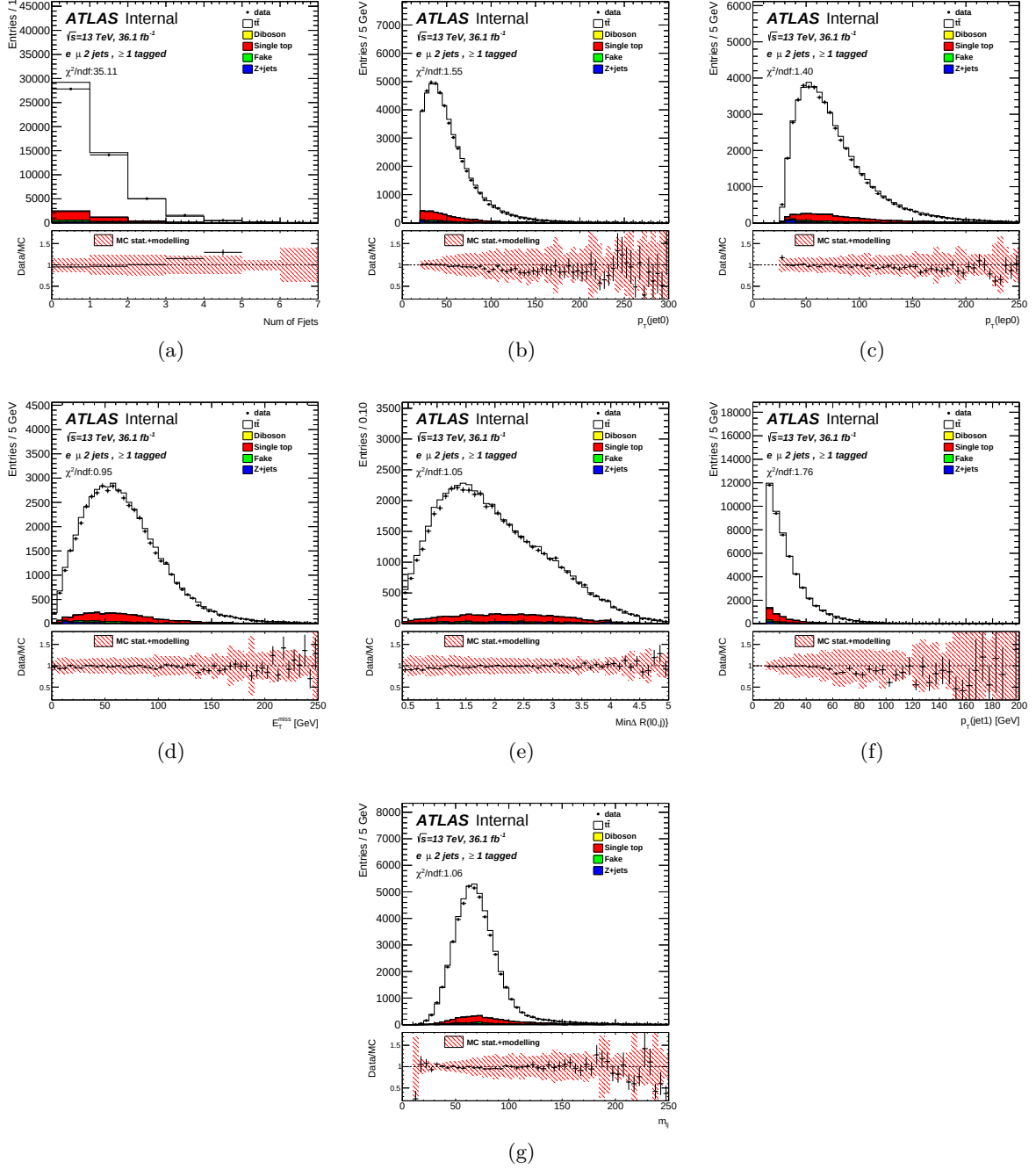


Figure 5.7 – Data/MC comparison of the distributions of the input variables of the *Purity* BDT, in the calibration of track jets, after having applied the tag-and-probe selection described in Sec. 5.2.4. From top to bottom, left to right: number of forward jets, p_T of the leading jet, p_T of the leading lepton, missing transverse energy, minimum ΔR separation between the leading lepton and all jets, p_T of the trailing jet, and lepton-jet invariant mass m_{lj} . The error band includes the MC statistical uncertainty and the modelling ($t\bar{t}$ single top and Z +jets) systematics uncertainty.

signal ($b\bar{b}$ pairs in $t\bar{t}$ events) and background, as found in an optimisation study. The correlation matrices between the input variables of the Purity BDT for signal and background for the calorimeter-jet calibration and the track-jet calibration are shown in Figures 5.10 and 5.11, respectively.

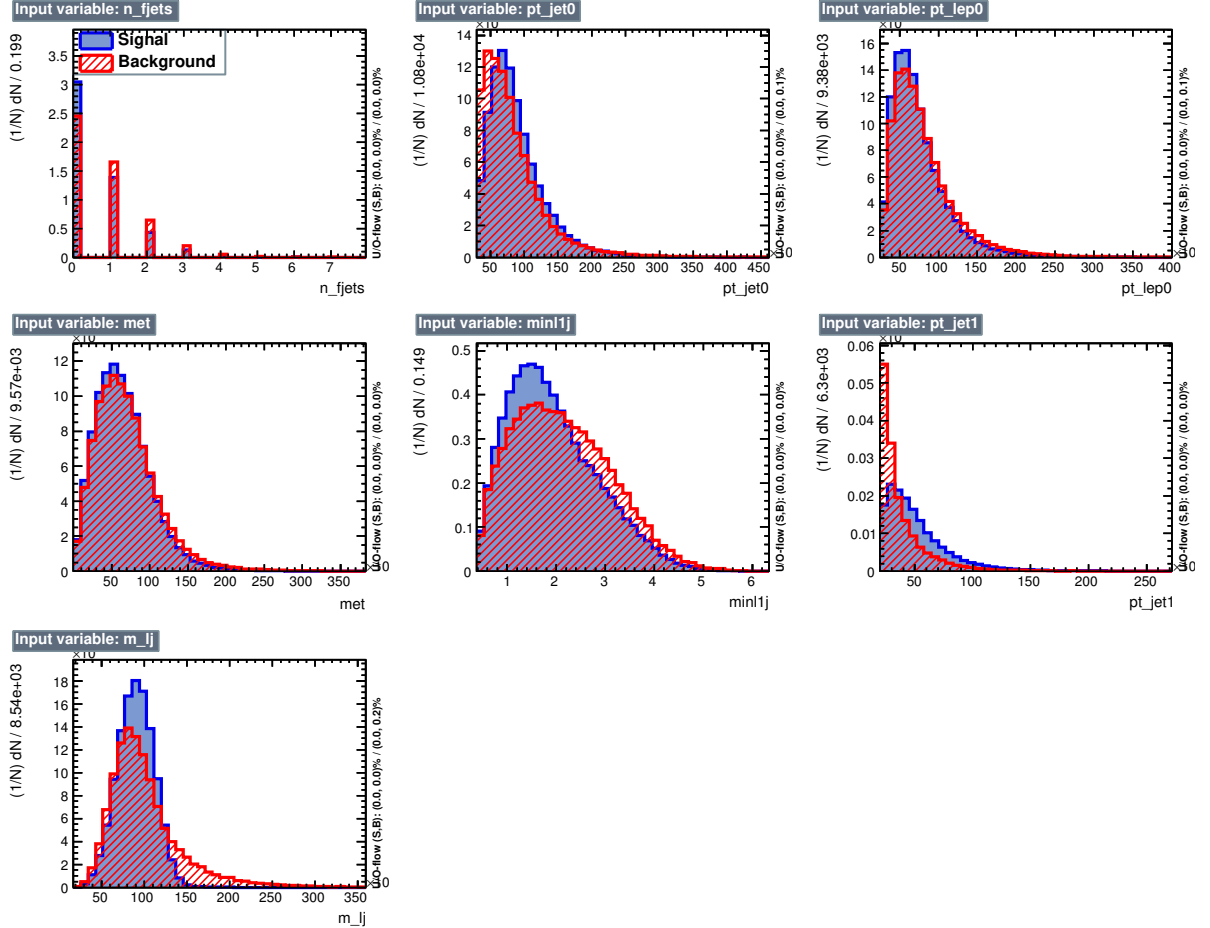


Figure 5.8 – Distributions of the input variables used for the *Purity* BDT, for signal (only $b\bar{b}$ pairs from $t\bar{t}$) and background (other jet pairs from $t\bar{t}$ and single top (Wt channel)) events in the calorimeter-jet calibration. The distributions of some additional variables not used in the final BDT are also shown.

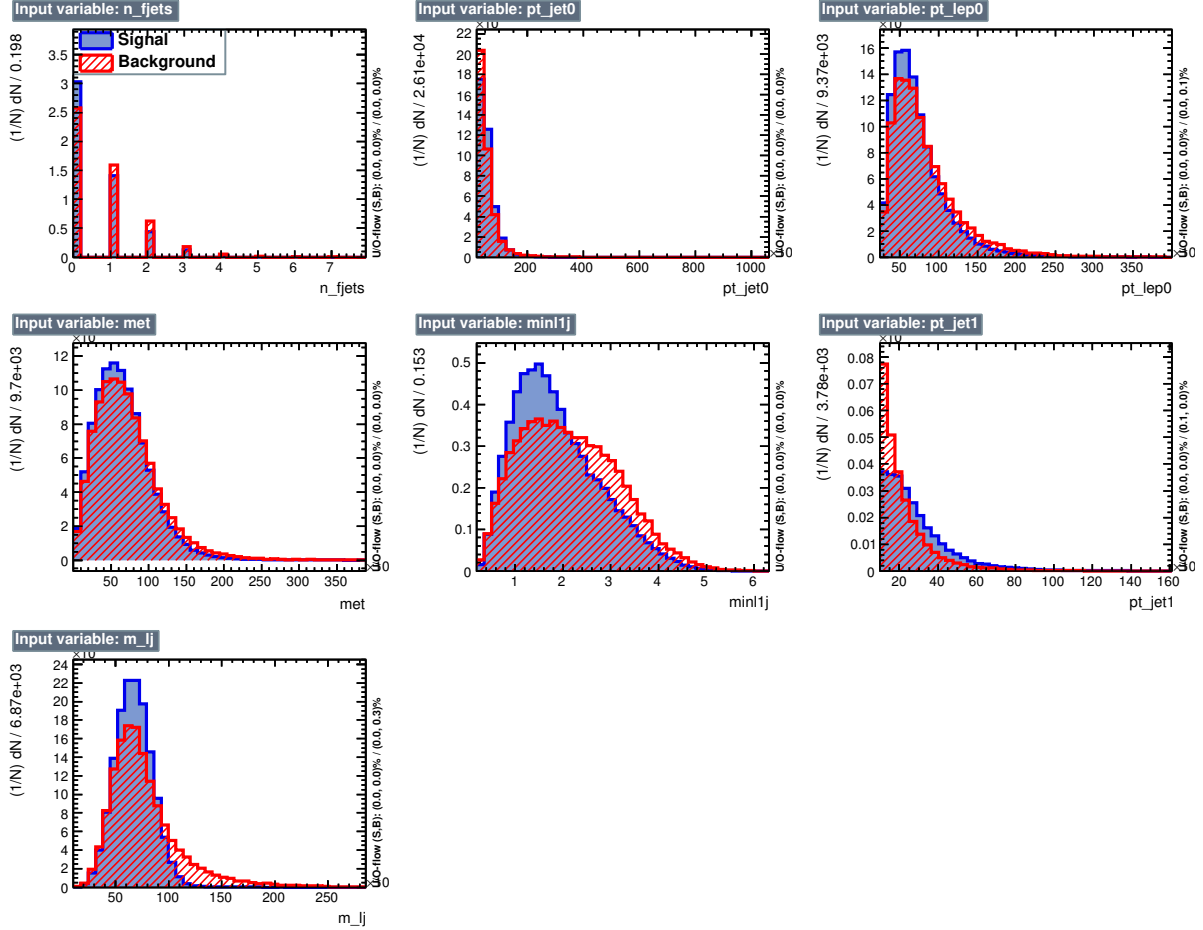


Figure 5.9 – Distributions of the seven input variables used for the *Purity* BDT, for signal (only $b\bar{b}$ pairs from $t\bar{t}$) and background (other jet pairs from $t\bar{t}$ and single top (Wt channel)) events in the track-jet calibration. The distributions of some additional variables not used in the final BDT are also shown.

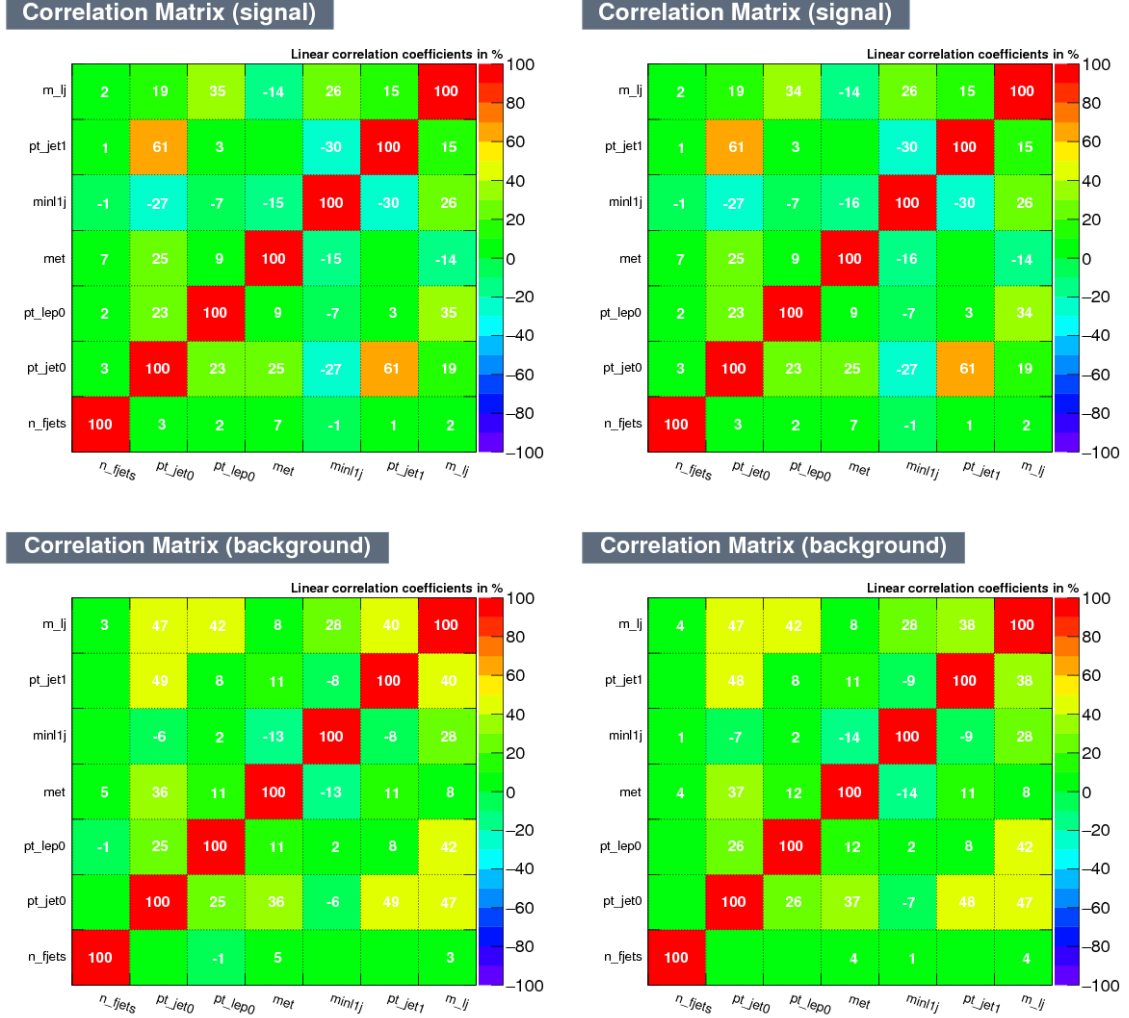
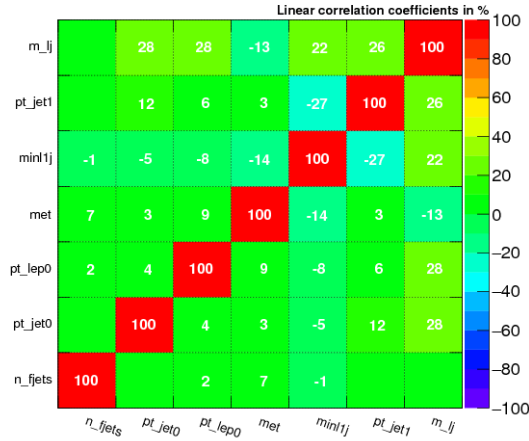
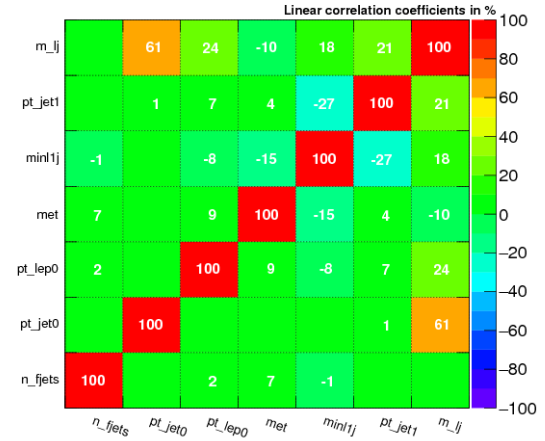


Figure 5.10 – Correlation matrices among the seven input variables of the Purity BDT for the calorimeter-jet calibration for signal (up) and background (down) events. The plots in the left (right) column use odd (even) events to train the BDT.

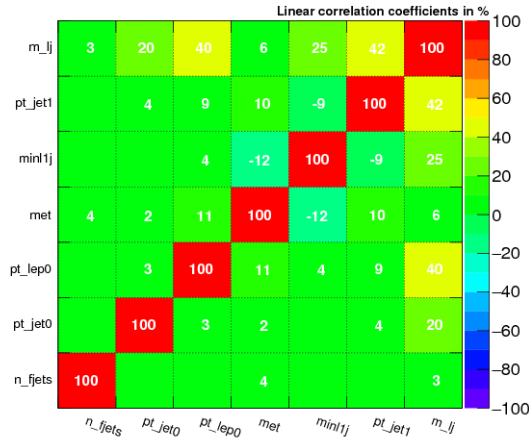
Correlation Matrix (signal)



Correlation Matrix (signal)



Correlation Matrix (background)



Correlation Matrix (background)

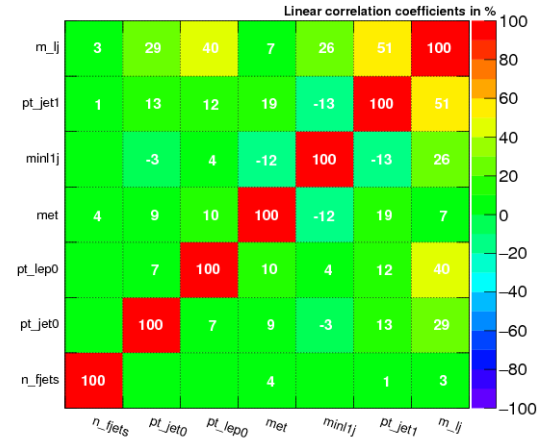


Figure 5.11 – Correlation matrices among the seven input variables of the Purity BDT for the track-jet calibration for signal (up) and background (down) events. The plots in the left (right) column use odd (even) events to train the BDT.

5.2.5.1 BDT Training

The training settings of the BDT are listed in Table 5.4. The chosen values of the NTrees, MinNodeSize, MaxDepth and nCuts parameters were found to give the best performance among a few different configurations with different settings that were tested.

Table 5.4 – Settings used for the training of the Purity BDT with TMVA.

Parameter	Value
NTrees	850
MinNodeSize	2.5%
MaxDepth	3
BoostType	AdaBoost
AdaBoostBeta	0.5
UseBaggedBoost	Yes
BaggedSampleFraction	0.5
SeparationType	GiniIndex
nCuts	20

A 2-fold approach is followed. The simulated $t\bar{t}$ and single-top samples are split into two subsets: even-numbered events and odd-numbered events. Two BDTs are then trained with either subset. In the event selection, for both MC and data, the BDT scores of even-numbered (odd-numbered) events are calculated with the BDT trained with odd (even) subset to avoid any possible selection bias. For each of the two BDTs, overtraining is checked by comparing the ROC curve of the sample used for training to that of the other sample, as shown in Fig. 5.12 and Fig. 5.13 for the calibration of calorimeter jets and track jets respectively. No strong indication of overtraining is observed.

The distribution of the BDT of selected events in data and in the simulation is shown in Fig. 5.14.

5.2.5.2 Optimisation of the requirement on BDT output

A requirement of the minimum value on the *Purity* BDT output is applied to improve the b -jet purity of the selected sample. A series of working points for such requirement has been tested. The working points correspond to a fixed cut on the value of the *Purity* BDT output, which corresponds to a nominal efficiency (varying between 60% and 100% depending on the chosen working point) for $b\bar{b}$ pairs selected in $t\bar{t}$ events. These working points are shown in Table 5.5.

As an illustration, the b -jet purity in various jet p_T bins of the selected probes in $t\bar{t}$ simulated events after applying the various working points is shown in Figure 5.15. After the BDT requirement, the b -jet purity increased significantly, especially in the high- p_T and low- p_T regions. For example, the b -jet purity increased relatively by +40% and +25% in the high- p_T and low- p_T regions for calorimeter jets.

For each working point the final uncertainty on the data/MC scale factor is estimated, including the systematic uncertainties described later, and the working point that is chosen is the one giving the smallest uncertainty on the b -tagging scale factor. Usually, working points with lower efficiency lead to a larger statistical uncertainty and to a smaller modelling systematic uncertainty due to the higher $b\bar{b}$ purity of the sample and reduce impact of the MC-based

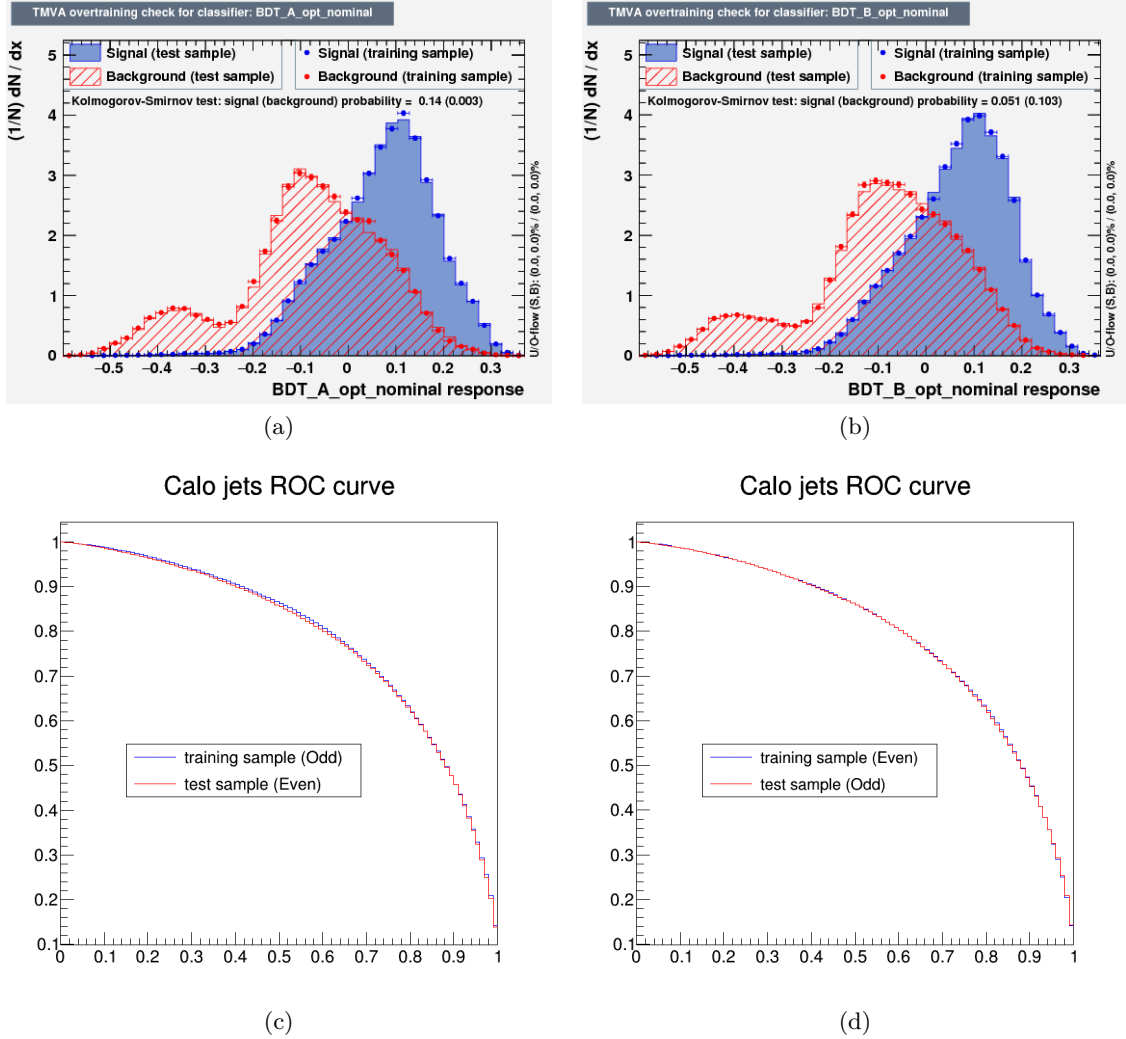


Figure 5.12 – Overtraining check for the *Purity* BDT of calorimeter jets. The top row shows the comparisons of the BDT output distributions and the bottom row the ROC curves. The results in the left column use the odd-numbered events for training and the even ones for test. The results in the right column use the even-numbered events for training and the odd ones for test.

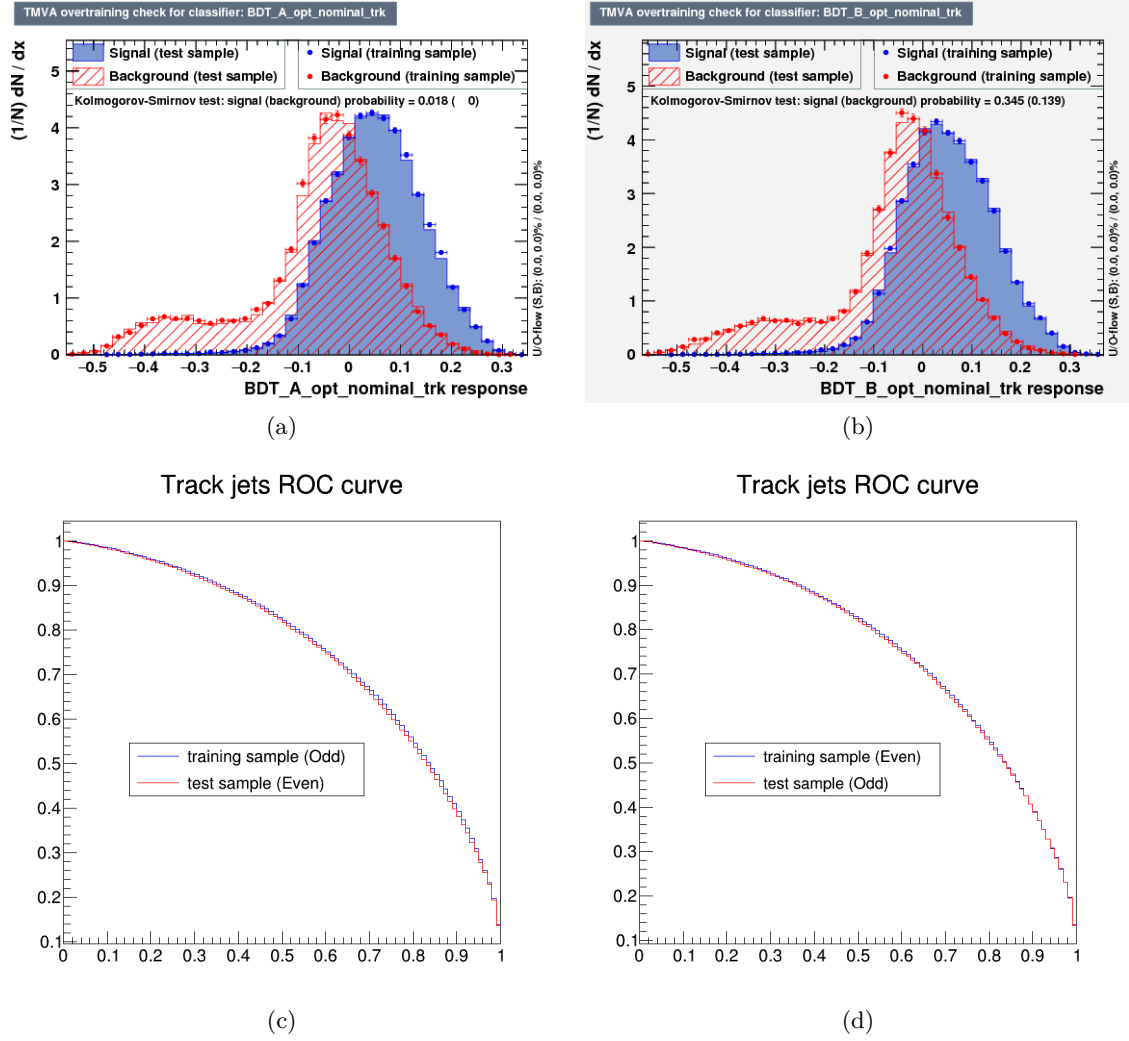


Figure 5.13 – Overtraining check for *Purity* BDT of track jets. The top row shows the comparisons of the BDT output distributions and the bottom row the ROC curves. The results in the left column are used the odd events for training and even for test. The results in the right column are used the even events for training and odd for test.

Table 5.5 – Cut points w.r.t to the efficiency of $b\bar{b}$ events in the $t\bar{t}$ simulation, from 60% to 100%, for calorimeter-jet and track-jet calibration respectively. The cut points for odd-numbered events are based on the BDT training with even-numbered events and vice versa.

Calorimeter-jet									
$b\bar{b}$ efficiency [%]	60	65	70	75	80	85	90	95	100
Odd-number events	0.0536	0.0376	0.0216	0.0008	-0.0216	-0.0488	-0.0808	-0.1240	-
Even-number events	0.0568	0.0408	0.0232	0.0008	-0.0216	-0.0488	-0.0792	-0.1208	-
Track-jet									
$b\bar{b}$ efficiency [%]	60	65	70	75	80	85	90	95	100
Odd-number events	0.0280	0.0168	0.0056	-0.0072	-0.0216	-0.0376	-0.0552	-0.0856	-
Even-number events	0.0296	0.0168	0.0040	-0.0088	-0.0232	-0.0408	-0.0600	-0.0888	-

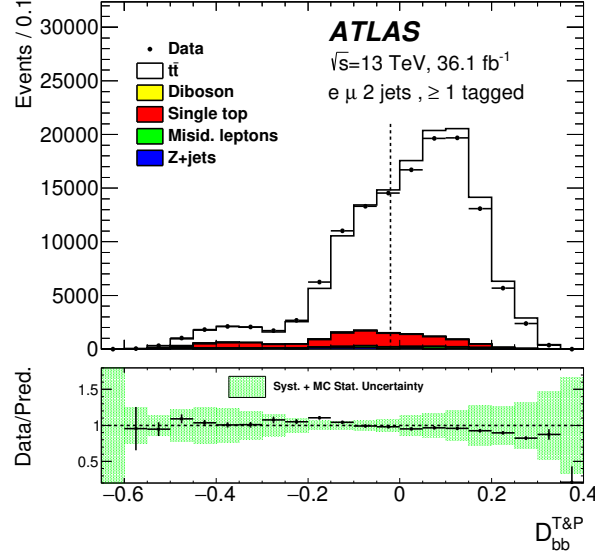


Figure 5.14 – The Purity BDT output distribution for the data (points) and simulated samples (stacked histograms) for the $e\mu + 2$ -jets sample used in the T&P calorimeter-jet b -tagging calibration. The normalisation of the simulated samples is taken from the theoretical predictions. The cut applied to the discriminant in the is indicated by a vertical dotted line. The bottom panel shows the ratio of the data to the simulated samples, with the shaded uncertainty bands corresponding to the total MC statistical uncertainty and systematic uncertainty.

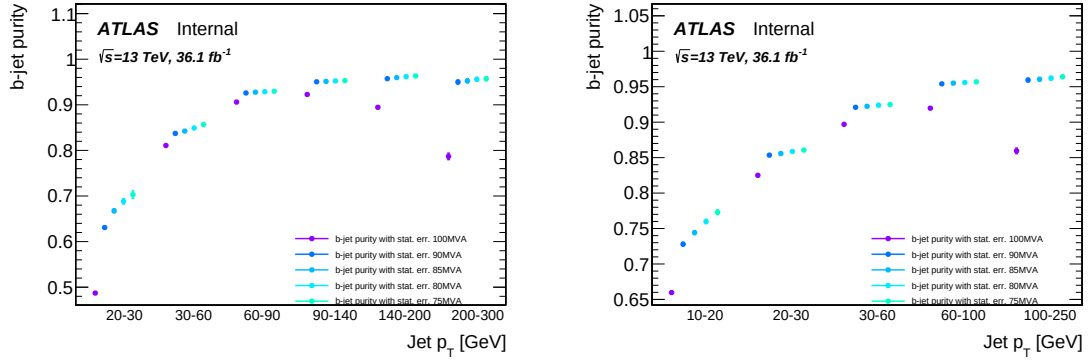


Figure 5.15 – The purity of b -jet from $t\bar{t}$ events in the selected probe sample after applying different requirements on the Purity BDT, for the calorimeter-jet calibration (left) and the track-jet calibration (right). XXMVA means that the requirement applied to the Purity BDT corresponds to a nominal efficiency of XX%.

corrections needed to measure the b -tagging efficiency. We observe that in general the 80% working point of the *Purity* BDT for the calorimeter-jet calibration and the 70% working point of the *Purity* BDT for the track-jet calibration provide the smallest total uncertainty in most of the p_T bins under study and we thus use those working points for the final results.

Figure 5.16 shows the fraction of b -jets as a function of p_T before and after applying the chosen requirement on the Purity BDT (> -0.02) for the nominal and alternative $t\bar{t}$ generators, in the calorimeter-jet calibration.

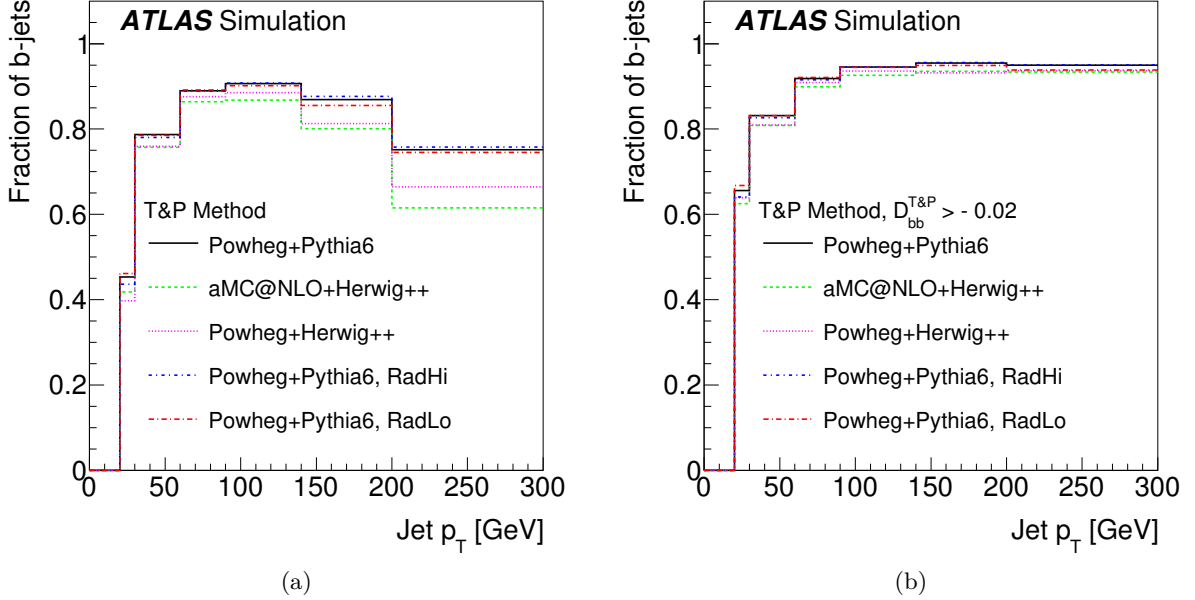


Figure 5.16 – The fraction of b -jets in the selected calorimeter-jet probe sample as a function of the jet p_T , (a) before and (b) after the requirement on the Purity BDT, for the nominal and alternative $t\bar{t}$ generators.

The p_T distribution of the probes selected in data after application of the Purity BDT requirement is shown in Figure 5.17.

The MV2c10 distribution of the calorimeter-jet probes selected in data and in the simulation after the application of the Purity BDT requirement is shown in Figure 5.18. In the simulation, the separate contribution of the different processes (Figure 5.18(a)) or of the different probe jet flavours (Figure 5.18(b)) are also shown.

The number of events in data for the calibration of calorimeter jets, after the application of the *Purity* BDT cut with 80% nominal efficiency for $b\bar{b}$ pairs is given in Table 5.6.

The number of events in data for the calibration of track jets, after the application of the *Purity* BDT cut with 70% nominal efficiency for $b\bar{b}$ pairs is given in Table 5.7.

5.2.6 Statistical uncertainties

In the b -tagging efficiency scale factor calculation of Equations (5.1)–(5.4), only the yields $N_{\text{data}}^{\text{pass}}$ and N_{data} are obtained from the data. Their uncertainties are thus propagated to the statistical uncertainty in the b -tagging efficiency, using an ensemble of ten thousand pseudo experiments to take into account their correlations, in the following way. For each pseudo experiment:

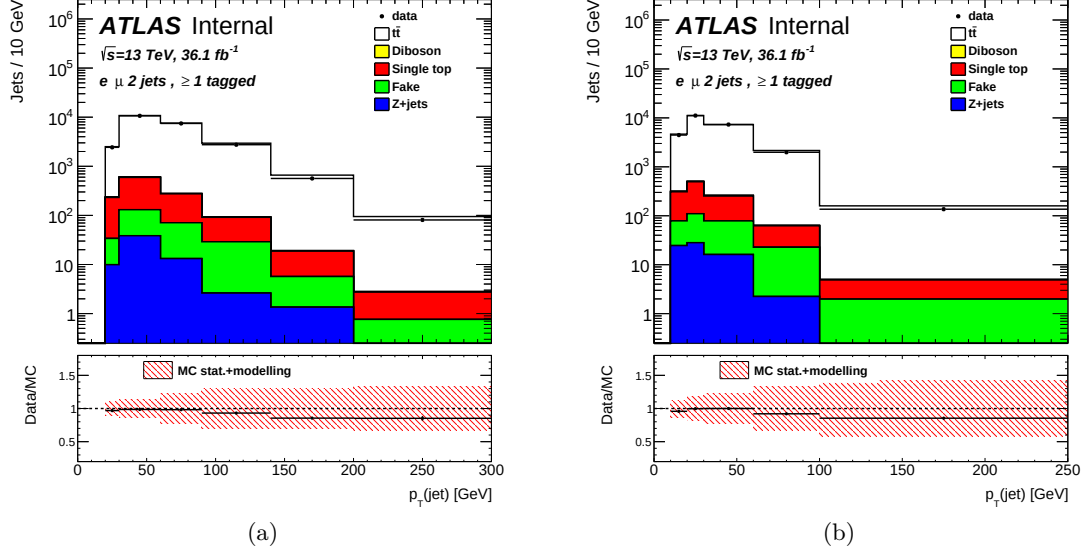


Figure 5.17 – The transverse momentum distributions of (a) the calorimeter-jet and (b) track-jet probes selected after having applied the Purity BDT requirement.

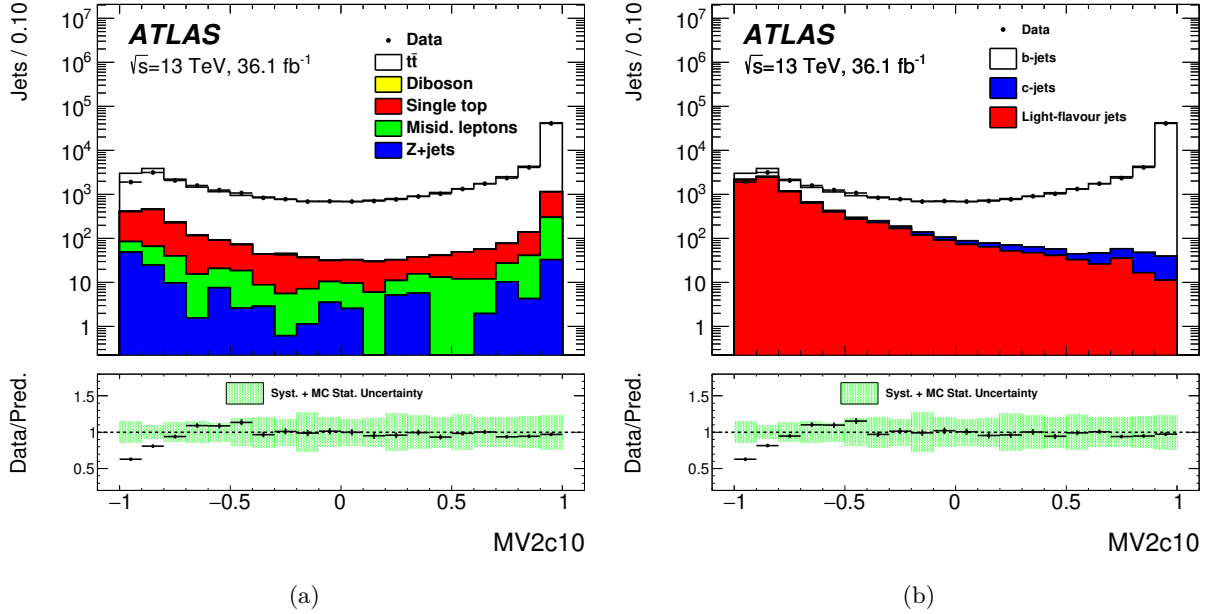


Figure 5.18 – The MV2c10 distribution of the probe jets used for the calorimeter-jet calibration, (a) broken down by process, and (b) probe jet flavour.

Table 5.6 – The number of events and the MC statistical uncertainty for calorimeter-jets calibration with *Purity* BDT cut at 80% working point.

	calorimeter-jets
diboson	55 ± 4
singletop	1981 ± 24
Z +jets	147 ± 21
$t\bar{t}$	45135 ± 130
fake leptons	436 ± 21
total MC	47755 ± 135
data	45675

Table 5.7 – The number of events and the MC statistical uncertainty for track-jets calibration with *Purity* BDT cut at 70% working point.

	track-jets
diboson	38 ± 3
singletop	994 ± 17
Z +jets	96 ± 14
$t\bar{t}$	27959 ± 102
fake leptons	286 ± 17
total MC	29374 ± 106
data	28299

- the number X of probes is obtained by sampling a Poisson distribution with mean N_{data}

$$X \sim \text{Poisson}(\lambda = N_{\text{data}}) \quad (5.6)$$

- the number Y of probes that pass the b -tagging requirement is obtained by sampling a binomial distribution corresponding to X total events and a passing rate:

$$\mathbf{p} = \frac{N_{\text{data}}^{\text{pass}}}{N_{\text{data}}} \quad (5.7)$$

$$Y \sim \text{Binomial}(X, \mathbf{p}) \quad (5.8)$$

- the efficiency is then computed using Equations (5.1)–(5.4), and the efficiency scale factor is obtained from the ratio between the data and the MC efficiency.

The standard error of the scale factor distribution in the ensemble of pseudoexperiments is used as the estimate of the statistical uncertainty in the measured scale factor.

5.2.7 Systematic uncertainties

Systematic uncertainties arise from the fact that some inputs of the measurement (Eqns. 5.1 and 5.2) are taken from the simulation, as mentioned in Sec. 5.2.2. They are thus known with limited accuracy, due to their statistical uncertainty originating from the limited size of the Monte Carlo samples, and to uncertainties on their production rates and their selection efficiency. In particular:

- in Eq. (5.1), the numbers $N_{\text{non-}t\bar{t}}$ and $N_{\text{non-}t\bar{t}}^{\text{pass}}$ of all probe jets not from $t\bar{t}$ events and of those that pass the b -tagging requirement are taken from the simulation. Both numbers are affected by uncertainties in:

1. the integrated luminosity;
2. the cross sections of the non- $t\bar{t}$ backgrounds;
3. the theoretical modelling of the non- $t\bar{t}$ backgrounds;
4. the reconstruction and selection efficiencies of the objects used in the event (leptons, jets, ..).

The $N_{\text{non-}t\bar{t}}^{\text{pass}}$ yield is also affected by uncertainties in

1. the b -tagging efficiency for light, charm and b -jets in non- $t\bar{t}$ events. In the measurement, the light and charm b -tagging efficiencies (*i.e.* mis-tag rates) are their uncertainties are propagated to the final measurement; for the efficiency of b -jets in non- $t\bar{t}$ events in Eq. (5.1), this is taken from the MC without any corrections and a generous 20% uncertainty (larger than the final uncertainty we determine on the b -tagging efficiency scale factors) is used to estimate the possible impact on the measurement.

- in Eq. (5.2), the fraction $f_b^{t\bar{t} \text{ MC}}$ of probe jets in the $t\bar{t}$ simulation that originate from a b quark, as well as the b -tagging efficiency for non b -jets predicted by the $t\bar{t}$ simulation, $\varepsilon_{\text{non-}b}^{t\bar{t} \text{ MC}}$, are used as inputs to obtain the final result. Such quantities are affected by:
 1. the theoretical modelling of $t\bar{t}$ production;
 2. the reconstruction and selection efficiencies of the objects used in the event (leptons, jets, ..).

In the following all these sources of systematic uncertainties are discussed and their impact on the final result is estimated.

5.2.7.1 Impact from the limited size of the simulation samples

A source of uncertainty in the measured scale factor that is statistical in nature is the limited size of the simulated samples. However, since it is not related to fluctuations in the data under study, it is considered here as part of the systematic uncertainty in the scale factors.

Such uncertainty is estimated with the same method for the statistical uncertainties in data. In this case, however, the numbers $N_{\text{data}}^{\text{pass}}$ and N_{data} are fixed to the yields observed in data, and the quantities that are sampled are the MC inputs of Equations (5.2) and (5.4). Those inputs are functions of the six yields summarized in Table 5.8.

Table 5.8 – The yields taken from the simulation and used as inputs for the calculation of the b -tagging efficiency scale factor. The “pass” yields indicate the number of (b or non- b) jet probes that pass the b -tagging requirement corresponding to the operating point of MV2c10 under calibration.

Parameters		Meaning
$N_{t\bar{t}}^b$	$N_{t\bar{t}}^{b,\text{pass}}$	b -jet probes in $t\bar{t}$ events: total number, and after the b -tagging requirement
$N_{t\bar{t}}^{\text{non-}b}$	$N_{t\bar{t}}^{\text{non-}b,\text{pass}}$	non- b -jet probes in $t\bar{t}$ events: total number, and after the b -tagging requirement
$N_{\text{non-}t\bar{t}}$	$N_{\text{non-}t\bar{t}}^{\text{pass}}$	probes in non- $t\bar{t}$ events: total number, and after the b -tagging requirement

In each pseudo experiment, the total number X of probes (b or non- b jets in $t\bar{t}$, or jets in non- $t\bar{t}$ events) is obtained by sampling a Gaussian distribution with mean N_{total} and width σ_{total} equal to the statistical uncertainty in N_{total} :

$$X \sim \text{Gaussian}(N_{\text{total}}, \sigma_{\text{total}}) \quad (5.9)$$

Given the passing rate:

$$\mathbf{p} = \frac{N_{\text{pass}}}{N_{\text{total}}} \quad (5.10)$$

the number Y of probes passing the b -tagging requirement is sampled from:

$$Y \sim \text{Gaussian}(X \cdot \mathbf{p}, \sigma_{\text{total}} \cdot \sqrt{\mathbf{p} \cdot (1 - \mathbf{p})}) \quad (5.11)$$

Again, the procedure is repeated ten thousand times. Each time the efficiency and the scale factor is computed, and finally the standard deviation of the scale factor distribution in the whole ensemble is taken as the systematic uncertainty due to the limited MC statistics.

5.2.7.2 Luminosity uncertainty

The luminosity uncertainty is estimated by varying its value by $\pm 3.2\%$ when scaling the simulation to the data in order to subtract the non- $t\bar{t}$ contribution from the selected events. It is determined in "Van-der-Meer" x - y beam separation scans, following the technique described in Ref. [96], performed in 2015 and 2016.

5.2.7.3 Uncertainties in the background cross sections

Theoretical uncertainties in the cross sections of the single-top Wt process (5.5%), Z +jets (20%) and diboson production (50%) [97] are propagated to the final result by varying the nominal cross sections of the simulated samples for such processes by their uncertainties.

5.2.7.4 MC modelling

The selected probe sample is dominated by $t\bar{t}$ and, to a lesser extent, single-top and Z +jets events. Since the measurement uses some inputs computed from the simulation, uncertainties in the modelling of these processes lead to (systematic) uncertainties on the measured efficiency.

The sources of modelling systematic uncertainties that have been considered are listed in Tables 5.9, 5.10, and 5.11. Each modelling systematic uncertainty is estimated in this way: the b -tagging efficiency scale factors are re-calculated after replacing the nominal $t\bar{t}$, single-top and Z +jets MC samples with the alternative one in the appropriate row of Tables 5.9, 5.10, and 5.11. The difference between the new scale factor and the nominal one is considered as the systematic uncertainty.

The $t\bar{t}$ and single-top uncertainties account for the uncertainties in the matrix element calculation for the generation of the hard scattering event, in the underlying event and parton shower, and in the amount of parton radiation. Dedicated $t\bar{t}$ uncertainties have also been calculated to account for the effect of PDF uncertainties and for the uncertainty on the top and $t\bar{t}$ p_T spectrum (the latter are calculated by comparing the results applying or not a reweighting of the top and $t\bar{t}$ p_T spectra to match NNLO predictions). An additional uncertainty on the single-top prediction accounts for the uncertainty in the overlap between Wt and $t\bar{t}$ events. Such overlap arises at NLO and is subtracted from the nominal Wt simulated samples with a diagram removal (DR) technique. The corresponding uncertainty is estimated by using single-top samples in which a diagram subtraction (DS) technique is used instead [98]. For Z +jet events, which constitute a very small fraction of the selected sample, the inclusive cross section uncertainty mentioned above and the uncertainty in the matrix element calculation are considered. For diboson events, which are even fewer, only the inclusive cross section uncertainty mentioned previously is considered, and no extra modelling uncertainty is evaluated.

Table 5.9 – The pairs of samples used to study the modelling systematic uncertainties for $t\bar{t}$ events, and the corresponding source of systematic uncertainty being tackled.

source of systematics	Tools/samples	
Hard Scatter Generation	Powheg+Herwig++	aMC@NLO+Herwig++
Fragmentation/Hadronization	Powheg+Pythia6	Powheg+Herwig++
PDF central value	aMC@NLO+Herwig++ with CT10 PDFs	aMC@NLO+Herwig++ with PDF4LHC15 NLO 100 PDFs
Additional Radiation	radhi:hdamp= $2 \times m_{top}$, scale=0.5	radlo:hdamp= $1 \times m_{top}$, scale=2

Table 5.10 – The pairs of samples used to study the modelling systematic uncertainties for single top (Wt) events, and the corresponding source of systematic uncertainty being tackled.

source of systematics	Tools/samples	
Hard Scatter Generation	Powheg+Herwig++	aMC@NLO+Herwig++
Fragmentation/Hadronization	PowHeg+Pythia6	PowHeg+Herwig++
Additional Radiation	radhi:hdamp= $2 \times m_{top}$,scale=0.5	radlo:hdamp= $1 \times m_{top}$,scale=2
$t\bar{t}$ diagram overlap	Powheg+Pythia6 Diagram Removal Scheme (nominal)	Powheg+Pythia6 Diagram Subtract Scheme

Table 5.11 – The pairs of samples used to study the modelling systematic uncertainties for Z +jets events, and the corresponding source of systematic uncertainty being tackled.

source of systematics	Tools/samples	
Hard Scatter Generation	MadGraph+Pythia8	Powheg+Pythia8

5.2.7.5 Z +heavy-flavour jets modelling

An extra modelling uncertainty is related to the fraction of Z +jet events with at least one heavy flavour (b , c) hadron, which is known to be difficult to accurately predict with a simulation. The Z +heavy-flavour jet yield is thus varied by $\pm 50\%$. The VH , $H \rightarrow b\bar{b}$ analysis described in the next chapter measures in data – in the phase space selected by that analysis – a scale factor of about 1.3 ± 0.1 , which is covered by this $\pm 50\%$ variation.

5.2.7.6 Light- and c -jet mis-tag rates

The mis-tag rates of light-/ c -jets in the simulation, which affect the $N_{\text{non-}t\bar{t}}^{\text{pass}}$ yield in Eq. (5.2), are corrected for the nominal results using the data/MC efficiency scale factors measured elsewhere, and the corresponding uncertainties are propagated to the systematic uncertainties in the measurement of b -tagging scale factors.

5.2.7.7 Detector-related uncertainties

Detector-related uncertainties are estimated by repeating the measurement after varying by $\pm 1\sigma$ the nuisance parameter associated with each decorrelated source of uncertainty. The differences between the result obtained after such variations and the nominal case are considered as the systematic uncertainty in the measured efficiency (or scale factor). Uncertainties arise from the jet and lepton efficiency and calibration (momentum scale and resolution) and from the calibration and resolution of the soft term of the missing transverse momentum. The sources of systematic uncertainties that have been considered are summarised in Tables 5.12–5.15. The uncertainties on the lepton and jet efficiencies and energy scale and resolution are determined from control samples selected in 13 TeV pp collisions. They are also propagated to the calculation of the missing transverse energy, for which additional uncertainties from the momentum scale, resolution and efficiency of the tracks not associated with any of the reconstructed objects (“soft term”) are also considered.

Table 5.12 – Muon-related sources of experimental systematic uncertainties that have been evaluated.

Muon-related source of systematic uncertainty
trigger efficiency uncertainty
reconstruction and identification efficiency uncertainty
isolation efficiency uncertainty
track-to-vertex association efficiency uncertainty
energy scale uncertainty
energy resolution uncertainty from muon system
energy resolution uncertainty from inner detector

Table 5.13 – Electron-related sources of experimental systematic uncertainties that have been evaluated.

Electron-related source of systematic uncertainty
trigger efficiency uncertainty
reconstruction efficiency uncertainty
identification efficiency uncertainty
isolation efficiency uncertainty
energy scale uncertainty
energy resolution uncertainty

Table 5.14 – Jet-related sources of experimental systematic uncertainties that have been evaluated.

Jet-related source of systematic uncertainty
energy scale uncertainty
additional energy scale uncertainty for b -jets
energy resolution uncertainty
JVT cut efficiency

Table 5.15 – E_T^{miss} -related and pile-up related sources of experimental systematic uncertainties that have been evaluated.

E_T^{miss} -related or pile-up related source of systematic uncertainty
E_T^{miss} track-based soft term related longitudinal resolution uncertainty
E_T^{miss} track-based soft term related transverse resolution uncertainty
pile up reweighting

5.2.7.8 Fake lepton background uncertainty

As shown in Figure 5.17 the contribution from fake-lepton background events to the selected probe sample is much less than 1% in all bins. The systematic uncertainty related to the normalization of such background is taken into account by scaling its yield up and down by $\pm 50\%$. The impact of this source of uncertainty on the final measurement of the b -tagging efficiency is very tiny.

5.2.8 Results

As shown in Section 5.2.5.2, the b -jet purity in $t\bar{t}$ events is strongly dependent on the cut point of *Purity* BDT. The higher b -jet purity will lead to some decrease of the modelling systematics, at the price of a smaller statistics and thus a larger statistical uncertainty. As mentioned before, an optimisation procedure has been put in place to choose the value of the cut on the *Purity* BDT, by repeating the calibration procedure for different values of the cut on the *Purity* BDT, and then choosing the ones that gives the smallest sum in quadrature of the statistical and systematic uncertainties on the b -tagging efficiency scale factors. The optimisation procedures for the calibration of the 70% b -tagging working point for calorimeter-jets and track-jets are illustrated in Figure 5.19 and in Figure 5.20, respectively.

In the following, tables with the measured efficiency scale factors and the breakdown of their uncertainties are shown. The scale factors have been determined using a requirement on the *Purity* BDT corresponding to an 80% (70%) efficiency for calorimeter (track) jets. Plots of the data and MC efficiencies and of their ratios (*i.e.* the scale factors) with their uncertainties are also shown. The tables and the plots are only given for the single-cut, 70% working point, but the measurements have been performed – for the benefit of ATLAS analyses using them – also for the other working points and for the flat-efficiency variant of the MV2c10 selection. The scale factors are generally consistent with unity, within uncertainties of at most 10% in the bins with largest systematic uncertainties (the lowest- p_T bin) or largest statistical uncertainties (the highest- p_T bin), while in the intermediate p_T region, most relevant for the VH , $H \rightarrow b\bar{b}$ search presented in the next chapter, the uncertainties are on the level of about 1%–4%.

5.2.8.1 Results of the calorimeter-jet calibration

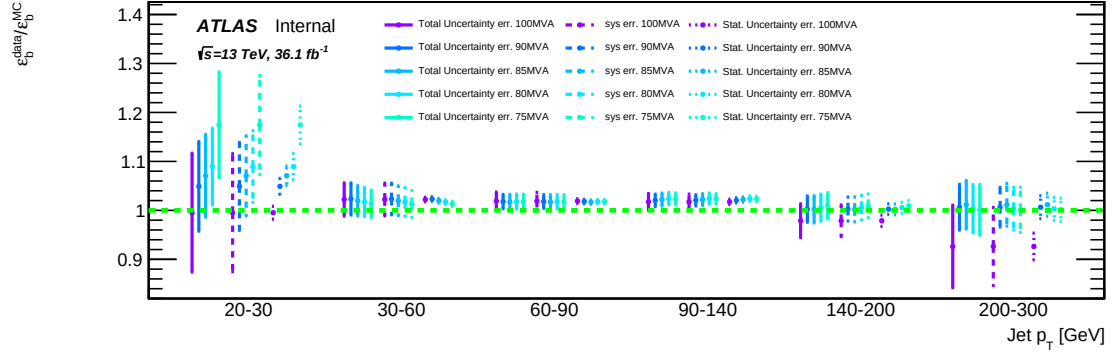
The measured efficiencies and scale factors as a function of the jet p_T are shown in Figure 5.21. The scale factors are consistent with unity within their uncertainties. The scale factors have also been measured as a function of the jet η and of the average number of interaction per bunch-crossing. No strong dependence on either variable was observed, with maximum variations of 1% over the range $1 < \langle \mu \rangle < 50$ and of 5% for $|\eta|$ varying between 0 and 2.5.

The measured b -tagging efficiency scale factors as a function of the jet p_T , together with their uncertainties and a detailed breakdown of the various contributions to the total uncertainties, are tabulated in Table 5.16.

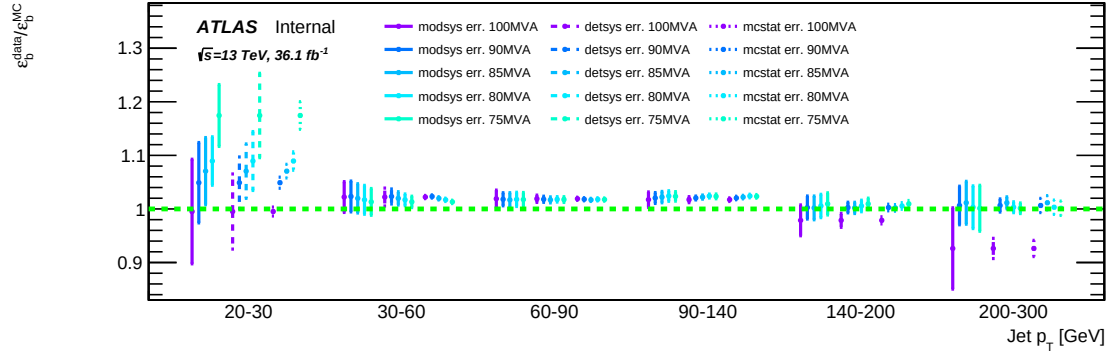
5.2.8.2 Results of the track-jet calibration

The measured efficiencies and scale factors as a function of the jet p_T are shown in Figure 5.22. The scale factors are consistent with unity within their uncertainties.

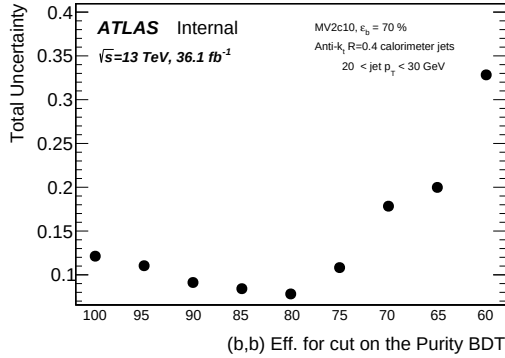
The measured b -tagging efficiency scale factors as a function of the jet p_T , together with their uncertainties and a detailed breakdown of the various contributions to the total uncertainties, are tabulated in Table 5.17.



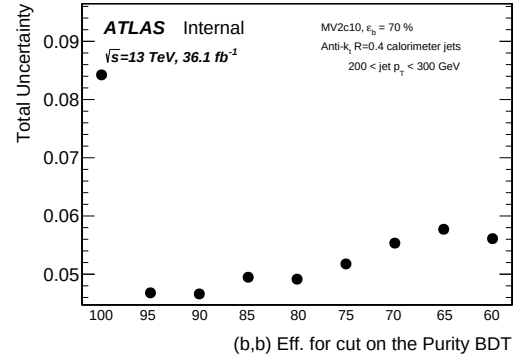
(a)



(b)

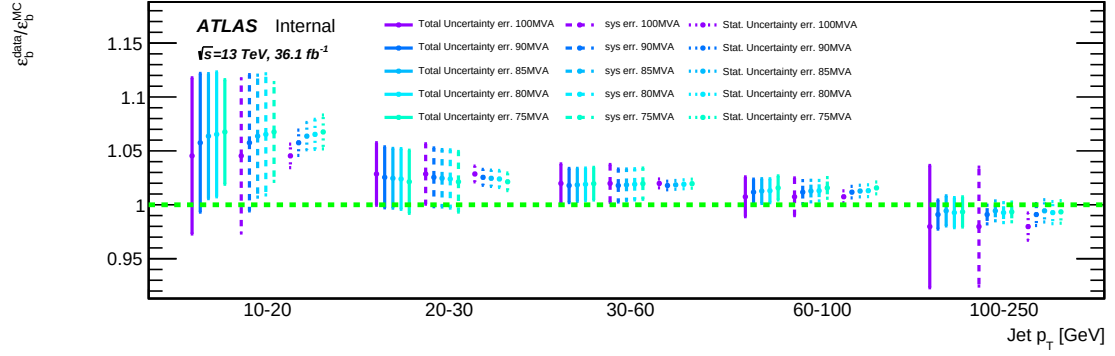


(c)

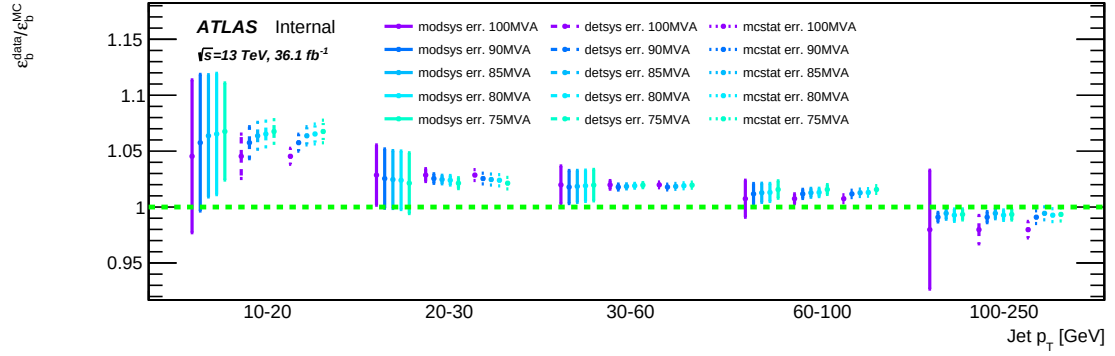


(d)

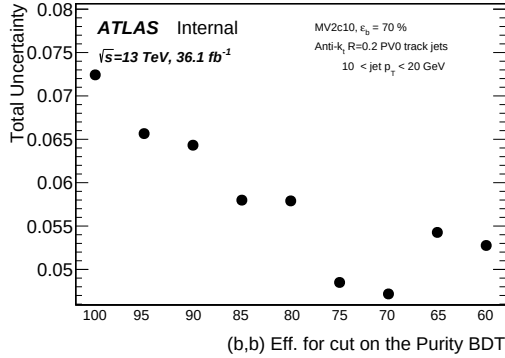
Figure 5.19 – The top plot shows the scale factors in each jet p_T bin with total uncertainty (solid line), systematic uncertainty (dashed line) and statistical uncertainty (in compact dashed line) with all tested *Purity* BDT cut points (different colors). To check the details in the systematic uncertainty, the systematic uncertainties are split into modelling systematic (dashed line), detector related systematic (compact dashed line) and systematic due to MC statistics (densely dotted line), as shown in the middle plot. The bottom two plots show the total uncertainties for the lowest p_T bin (left) and the highest p_T bin (right) to check the details of the total uncertainties in these two bins. The results are shown for calorimeter-jet b -tagging calibration of the single-cut working point at 70% b -jet efficiency.



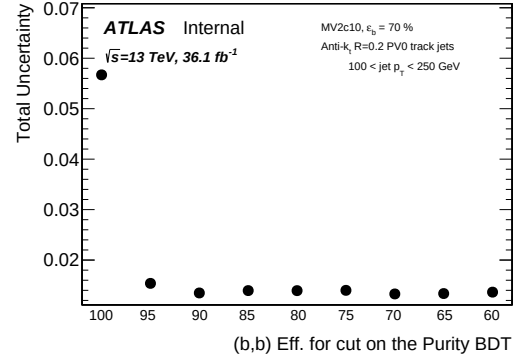
(a)



(b)



(c)



(d)

Figure 5.20 – The top plot shows the scale factors in each jet p_T bin with total uncertainty (solid line), systematic uncertainty (dashed line) and statistical uncertainty (compact dashed line) with all tested *Purity* BDT cut point (different colors). To check the details in the systematic uncertainty, the systematic uncertainties are split into modelling systematic (dashed line), detector related systematic (compact dashed line) and systematic due to MC statistics (densely dotted line), as is shown in the middle plot. The bottom two plots show the total uncertainties for the lowest p_T bin (left) and the highest p_T bin (right) to check the details of the total uncertainties in these two bins. The results are shown for track-jet b -tagging calibration of the single-cut working point at 70% b -jet efficiency.

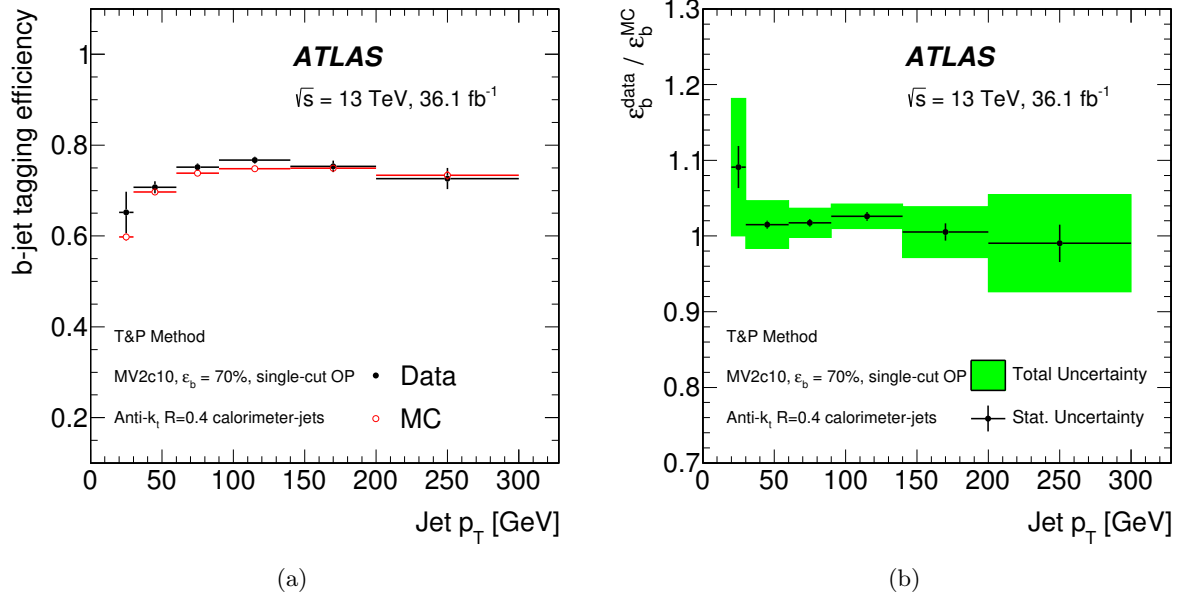


Figure 5.21 – (a) b -tagging efficiency comparison between data (in black) and simulation (in red). The total uncertainties are shown. (b) b -tagging efficiency scale factors with total uncertainty (in green) and with statistical uncertainty only (error bars). The b -tagging efficiency refers to calorimeter-jets and the single-cut 70% MV2c10 working point.

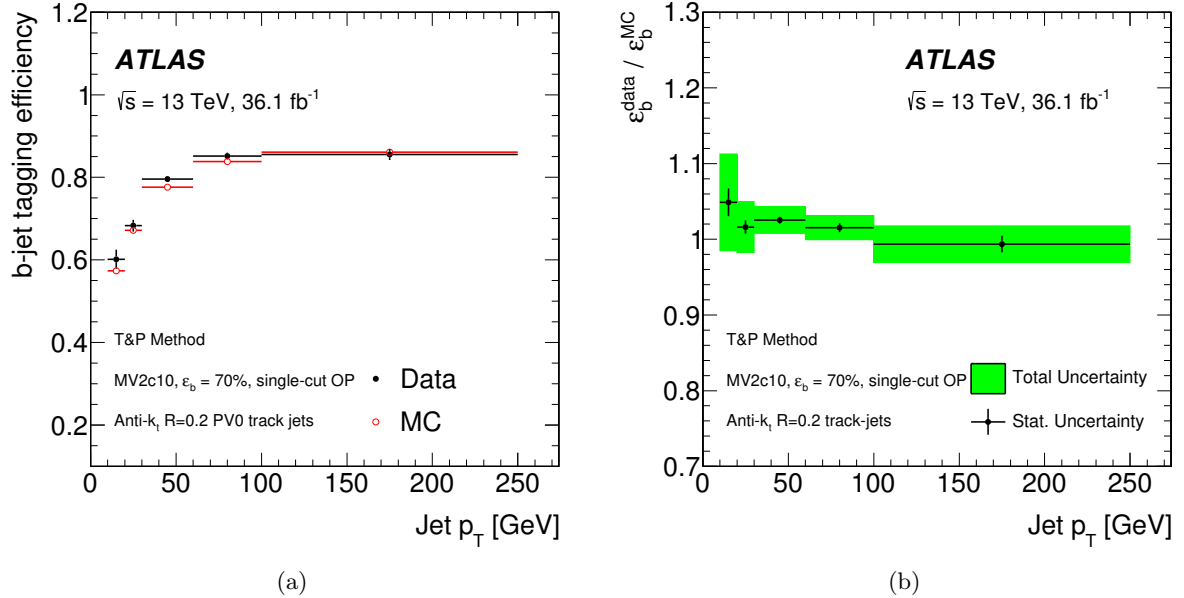


Figure 5.22 – (a) b -tagging efficiency comparison between data (in black) and simulation (in red). The total uncertainties are shown. (b) b -tagging efficiency scale factors with total uncertainty (in green) and with statistical uncertainty only (error bars). The b -tagging efficiency refers to track-jets and the single-cut 70% MV2c10 working point.

Table 5.16 – Data-to-simulation scale factors and associated uncertainties for the 70% b -tagging efficiency single-cut operating point of the MV2c10 b -jet tagging algorithm, for $R = 0.4$ calorimeter-jets, as a function of the jet p_T .

Calorimeter jets, 70% single-cut MV2c10 working point						
p_T interval [GeV]	20–30	30–60	60–90	90–140	140–200	200–300
Scale factor	1.091	1.015	1.017	1.026	1.005	0.990
Total uncertainty	0.091	0.032	0.019	0.016	0.034	0.064
Statistical uncertainty	0.028	0.005	0.005	0.006	0.011	0.025
Systematic uncertainty	0.086	0.031	0.019	0.015	0.032	0.059
Systematic Uncertainties [%]						
Matrix element modelling ($t\bar{t}$)	2.6	0.5	1.1	0.8	1.3	3.5
Parton shower / Hadronisation ($t\bar{t}$)	2.0	2.1	0.7	0.4	1.9	1.8
NNLO top p_T , $t\bar{t}$ p_T reweighting ($t\bar{t}$)	0.2	0.2	0.1	0.1	0.1	0.2
PDF reweighting ($t\bar{t}$)	2.9	0.6	0.6	0.7	1.3	2.2
More / less parton radiation ($t\bar{t}$)	3.8	1.7	0.8	0.7	0.7	2.8
Matrix element modelling (single top)	1.1	0.2	0.3	0.2	0.5	0.9
Parton shower / Hadronisation (single top)	1.1	0.2	0.2	0.2	0.5	0.9
More / less parton radiation (single top)	1.1	0.2	0.2	0.3	0.5	1.0
DR vs. DS (single top)	1.1	0.2	0.2	0.2	0.5	1.0
Modelling (Z +jets)	1.1	0.2	0.2	0.2	0.5	0.9
Limited size of simulated samples	1.6	0.3	0.3	0.3	0.6	1.4
Normalisation single top	0.3	0.1	0.1	0.0	0.0	0.0
Normalisation Z +jets	0.0	0.0	0.0	0.0	0.0	0.0
Normalisation $Z + b/c$	0.1	0.1	0.1	0.0	0.1	0.0
Normalisation diboson	0.1	0.1	0.0	0.0	0.0	0.0
Normalisation misid. leptons	0.3	0.1	0.0	0.1	0.1	0.1
Pile-up reweighting	1.9	0.4	0.4	0.2	0.7	0.9
Electron efficiency/resolution/scale/trigger	0.0	0.0	0.0	0.0	0.1	0.0
Muon efficiency/resolution/scale/trigger	0.3	0.0	0.0	0.0	0.0	0.0
E_T^{miss}	0.2	0.0	0.0	0.0	0.0	0.0
JVT	0.1	0.0	0.0	0.0	0.0	0.0
Jet energy scale (JES)	3.8	0.7	0.3	0.3	0.7	0.3
Jet energy resolution (JER)	1.5	0.5	0.2	0.1	0.2	0.7
Light-flavour jet mis-tag rate	0.2	0.0	0.1	0.0	0.1	0.0
c -jet mis-tag rate	0.1	0.0	0.0	0.0	0.0	0.0
Luminosity	0.2	0.1	0.0	0.0	0.0	0.0

Table 5.17 – Data-to-simulation scale factors and associated uncertainties for the 70% b -tagging efficiency single-cut operating point of the MV2c10 b -jet tagging algorithm, for $R = 0.4$ calorimeter-jets, as a function of the jet p_T .

Track jets, 70% single-cut MV2c10 working point					
p_T interval [GeV]	10–20	20–30	30–60	60–100	100–250
Scale factor	1.046	1.018	1.022	1.016	0.993
Total uncertainty	0.047	0.030	0.016	0.012	0.013
Statistical uncertainty	0.018	0.008	0.004	0.006	0.011
Systematic uncertainty	0.044	0.029	0.015	0.011	0.008
Systematic Uncertainties [%]					
Parton shower / Hadronisation ($t\bar{t}$)	3.3	1.9	0.4	0.5	0.1
Matrix element modelling ($t\bar{t}$)	0.5	0.2	0.9	0.1	0.0
NNLO Top p_T , $t\bar{t}$ p_T reweighting ($t\bar{t}$)	0.2	0.2	0.1	0.1	0.1
PDF reweighting ($t\bar{t}$)	0.2	0.0	0.2	0.1	0.0
More / less parton radiation ($t\bar{t}$)	1.9	2.0	1.0	0.7	0.3
Matrix element modelling (single top)	0.2	0.3	0.2	0.5	0.9
Parton shower / Hadronisation (single top)	0.2	0.1	0.1	0.1	0.0
More / less parton radiation (single top)	0.0	0.3	0.2	0.1	0.2
DR vs. DS (single top)	0.1	0.1	0.1	0.0	0.1
Modelling (Z +jets)	0.1	0.1	0.1	0.0	0.0
Limited size of simulated samples	1.1	0.5	0.3	0.3	0.6
Normalisation single top	0.1	0.1	0.0	0.0	0.0
Normalisation Z +jets	0.1	0.0	0.0	0.0	0.0
Normalisation $Z + b/c$	0.2	0.1	0.1	0.1	0.1
Normalisation diboson	0.1	0.1	0.1	0.0	0.0
Normalisation misid. leptons	0.1	0.1	0.1	0.1	0.1
Pile-up reweighting	0.5	0.2	0.2	0.4	0.4
Electron efficiency/resolution/scale/trigger	0.1	0.0	0.0	0.0	0.0
Muon efficiency/resolution/scale/trigger	0.1	0.0	0.0	0.0	0.0
E_T^{miss}	0.0	0.0	0.0	0.0	0.0
JVT	0.0	0.0	0.0	0.0	0.0
Jet energy scale (JES)	0.4	0.1	0.0	0.0	0.1
Jet energy resolution (JER)	0.1	0.0	0.0	0.1	0.0
Light-flavour jet mis-tag rate	0.8	0.3	0.1	0.0	0.1
c -jet mis-tag rate	0.3	0.1	0.0	0.0	0.0
Luminosity (3.2%)	0.1	0.1	0.0	0.0	0.0

Chapter 6

Evidence of VH , $H \rightarrow b\bar{b}$ production

As shown in chapter 2, the associated production mode of a Higgs boson with a vector boson V is – among the main Higgs boson production modes – the only one not firmly established yet in the past years. Similarly, among the Higgs boson decays with largest branching ratios, the one to $b\bar{b}$ – despite being the most probable one – had not been discovered before summer 2018. Observing the associated production VH of Higgs bosons decaying to $b\bar{b}$ with the ATLAS Run 2 data has thus been the purpose of my Ph.D. research activity.

The results of the study based on 36 fb^{-1} of data collected in 2015 and 2016 were released by the ATLAS Collaboration in summer 2017. They were shown at the European Physical Society (EPS) conference and then published in Journal of High Energy Physics [23]. For a Higgs boson mass of 125 GeV, an excess of events over the expected background from other Standard Model processes was found with an observed significance of 3.5 standard deviations (3.6σ after combination with Run 1 data) and a yield in good agreement with the SM Higgs boson predictions. This result, together with similar one (with 3.8σ significance) presented by the CMS Collaboration on the same timescale [99], constituted a strong evidence for the Higgs boson decay into pairs of b quarks and for its production in association with a vector boson. This analysis will be denoted in the following as the “EPS 2017 analysis”.

Recently, the ATLAS measurement has been updated to include also the additional 44 fb^{-1} of pp collisions collected in 2017; the results have been presented at the ICHEP 2018 conference [100] and are now published in Physics Letters B [24]. An excess of events over the SM background, corresponding to a significance of 4.9σ and in good agreement with the SM Higgs boson predictions, is observed. The combination with other ATLAS searches of $H \rightarrow b\bar{b}$ decays provides a combined measurement of the $H \rightarrow b\bar{b}$ branching ratio (assuming SM Higgs boson production cross sections) with a 5.4σ significance, constituting an observation of $H \rightarrow b\bar{b}$ decays. The combination with other ATLAS searches of VH production leads to a combined measurement of its cross section (assuming SM Higgs boson branching ratios) with a 5.3σ significance, constituting an observation of VH production.

In the following sections of this chapter, the EPS 2017 analysis will be presented, while the more recent results and the future prospects are deferred to the next chapter. The sections will describe the overall analysis strategy, the various analysis steps, and the results.

6.1 Overview of the EPS 2017 analysis

The Higgs boson decays to b quark pairs are searched for, in this analysis, in the vector-boson associated production mode VH , with the vector boson V ($V = W, Z$) decaying to leptons. Due

to the very large QCD multi-jet production cross section, the VH , $V \rightarrow \text{leptons}$ production mode offers the best sensitivity for the search of $H \rightarrow b\bar{b}$ events. The lower production cross section than gluon-fusion, VBF, or VH production followed by hadronic decays of the vector boson V is compensated by the much higher rejection of the backgrounds provided by the requirement of an identified charged lepton or of large transverse momentum imbalance due to the neutrinos in the final state.

Only vector boson decays producing electrons, muons and neutrinos (reconstructed in the detector as large $E_{\text{T}}^{\text{miss}}$) are searched for. Decays producing tau leptons are not targeted explicitly, but events in which at least one τ decays leptonically (branching ratio around 35%) still pass the selection. Events in which the tau leptons decay to hadrons and neutrinos of low transverse momentum are not selected; the signal-to-background ratio of such events is quite smaller than for the other final states under study. The analysis thus targets $e\nu$, $\mu\nu$ and $\tau(\rightarrow e, \mu)\nu$ decays of the W boson ($BR \approx 25\%$), and $\nu\nu$, ee , $\mu\mu$, $\tau(\rightarrow e, \mu)\tau$ decays of the Z boson ($BR \approx 28\%$).

The analysis is performed in parallel on the three sub-samples of events classified according to the number of selected charged leptons: 0, 1, or 2. The 0-lepton selection targets mainly ZH , $Z \rightarrow \nu\nu$ events, with a small (1–2%) contamination from WH , $W \rightarrow \ell\nu$ events where the lepton ℓ is outside the detector acceptance or does not pass the selection criteria. Similarly, the 1-lepton selection targets mainly WH , $W \rightarrow \ell\nu$ events, with a small (few %) contamination from ZH , $Z \rightarrow \ell\ell$ events. The 2-lepton selection targets ZH , $Z \rightarrow \ell\ell$ events. The event selection includes a part common to all the three final states, which is based on the properties of the Higgs boson decay products, and specific requirements that are different for each final state.

To reduce backgrounds from processes producing light jets, the jet candidates from the Higgs boson decay are required to pass b -tagging requirements. Topological selections are applied to suppress QCD heavy-flavoured jet production. After such requirements, the main backgrounds for the signal under search are:

- production of a vector boson in association with b -jets, with the vector boson decaying to leptons;
- production of a top-quark pair, with one or two W bosons from $t \rightarrow Wb$ decaying to leptons;
- diboson production, VZ , followed by a $Z \rightarrow b\bar{b}$ decay.

The b -quark pairs produced by such processes are not resonant, and their invariant mass, denoted as $m_{b\bar{b}}$, provides a powerful discriminating variable between such backgrounds and the signal, for which the $m_{b\bar{b}}$ distribution instead is peaked around the Higgs boson mass. Other kinematic quantities offer further separation between signal and background, and are combined with $m_{b\bar{b}}$ in a boosted decision tree (BDT), BDT_{VH} , which is trained on simulated signal and background events. A fit to the distribution of BDT_{VH} in data is then performed to extract the signal and background yields.

Subleading but non-negligible backgrounds originate from:

- vector boson production in association with charm and light jets, due to the non negligible mistag rate of the b -tagging algorithm;

- single-top production in association with a W boson, Wt , with one of the two W bosons in the event decaying to leptons, and a light-flavoured jet misidentified as a b -jet;
- QCD multi-jet production, in the 1-lepton channel.

Their contributions are also taken into account in the final fit.

To increase the sensitivity of the search, events are classified into categories with different $S/\sqrt{S+B}$. Events with different numbers of charged leptons (0, 1, 2) are analysed separately, and further categorised according to the number of jets N_{jet} in the event and – for 2-lepton events only – the transverse momentum of the vector boson, denoted as $p_{\text{T}}(V)$ or p_{T}^V in the following.

The results of the analysis are validated with two cross-checks. The first one, also called the *diboson analysis* in the following, consists in using the same procedure to determine the cross section of a relatively abundant and theoretically well known process similar to the signal, the production of VZ , $Z \rightarrow b\bar{b}$ events. Good agreement between the observed and expected yields for this process would reinforce the confidence in the use of a similar strategy for the determination of the background yields in data and the extraction of the VH signal yield. The second cross-check, also called the *dijet-mass analysis* in the following, consists in extracting the VH signal yield through a fit to the two b -jet invariant mass distribution, after having applied some additional selections on the other variables used in the BDT_{VH} discriminant. Such analysis is less sensitive than the nominal one but allows an easier visualisation of the signal, which is expected to induce a peak around 125 GeV in the dijet invariant mass distribution.

The EPS 2017 analysis is described in detailed in the following sections. The data and simulated samples used for the measurement are detailed in sections 6.2 and 6.3. The event selection and categorisation are given in sections 6.4 and 6.5. The BDT discriminant used in the final fit is described in section 6.6. The estimation from data of the multi-jet QCD background is outlined in section 6.7. The main systematic uncertainties are illustrated in section 6.8, and the fit used to extract the signal and background yields from the data in section 6.9; its results are given in section 6.10. The diboson and dijet-mass cross-checks are shown in sections 6.11 and 6.12.

6.2 Data sample

Proton-proton collisions at a center-of-mass energy of 13 TeV were collected by the ATLAS detector during the LHC Run 2, in 2015 and 2016. Only events in which all subdetectors were operating well and data quality is good are kept for subsequent analysis. Events were recorded by one of the following triggers:

- in the 0-lepton channel, events were recorded using $E_{\text{T}}^{\text{miss}}$ triggers with nominal thresholds of 70 GeV in 2015, and of 110 GeV in 2016. Due to the poor online $E_{\text{T}}^{\text{miss}}$ resolution, the efficiency of such triggers as a function of the $E_{\text{T}}^{\text{miss}}$ reconstructed offline grows slowly, with a turn-on curve that – for the trigger used in 2016 – reaches almost 100% only for $E_{\text{T}}^{\text{miss}} > 180$ GeV. The trigger efficiency is 85–90% at $E_{\text{T}}^{\text{miss}} = 150$ GeV.
- in the 1-lepton electron sub-channel, events were recorded using the lowest- p_{T} threshold unscaled single electron triggers. They apply isolation and identification requirements

that are looser than those used in the analysis. The nominal p_T threshold was 24 GeV in 2015 and 26 GeV in 2016; the electron trigger resolution is sufficiently good that the trigger is fully efficient for reconstructed electrons with offline p_T at least one GeV higher than the nominal online threshold.

- in the 1-lepton muon sub-channel, events were recorded using the same E_T^{miss} triggers used for the 0-lepton channel, exploiting the presence of the neutrino from the $W \rightarrow \mu\nu$ decay. This choice, which might seem counterintuitive, is due to the fact that the single muon trigger has a reduced acceptance (around 80%) due to the fast muon chambers covering only the region $|\eta| < 2.4$, with some gaps (particularly at $|\eta| < 0.1$) needed for the services of the inner subdetectors. The E_T^{miss} trigger on the other hand is found to provide a 98% acceptance for the signal. This is due to the fact that the offline selection applies a $p_T(V) > 150$ GeV requirement, where $p_T(V)$ is computed from the muon transverse momentum and the E_T^{miss} vector, and at trigger level – since muons are not included in the online E_T^{miss} calculation – the trigger is in effect selecting events based on $p_T(V)$ and is fully efficient for values of $p_T(V)$ above 180 GeV and rather highly efficient also for $150 < p_T(V) < 180$ GeV.
- in the 2-lepton channel, events were recorded using the lowest- p_T threshold unrescaled single electron and muon triggers. Similarly to the electron trigger, the muon trigger includes isolation and identification requirements that are looser than those applied offline. The nominal muon p_T threshold was 20 GeV in 2015 and 24 GeV in 2016; the muon momentum resolution in the trigger system is sufficiently good that the trigger is fully efficient for reconstructed muons with offline p_T at least one GeV higher than the nominal online threshold.

The integrated luminosity of the selected data sample is 36 fb^{-1} , and the average number of pp inelastic collisions per bunch crossing is 25.

6.3 Simulated samples

For the optimisation of the analysis criteria and to determine the expected signal and background distributions of the discriminant used in the final fit, simulated samples of the signal and of the main background processes are produced and studied. The only exception are QCD multi-jet events, since their production cross section and the rejection of such events by the analysis selection are so large that a prohibitively huge number of simulated multi-jet events would need to be generated, in order to obtain enough candidates passing all the requirements of the analysis. Such background is estimated using data-driven techniques, as described in section 6.7.

The samples are produced with state-of-the-art Monte Carlo event generators. In some cases, the events that are produced are filtered in order to keep only those with a high probability to pass the selection requirements, in order to maximise the equivalent luminosity of the sample for the same number of simulated events. For all samples, except those generated with SHERPA, the EVTGEN v1.2.0 program is used to model the decay of bottom and charm hadrons. The generated events passing the filter (if any) are passed to a detailed simulation of the ATLAS detector response based on Geant 4. The detector simulation is quite slower than the event

generation, and for this reason it is convenient to simulate the interaction with the ATLAS detector only of the events that are likely to pass the full analysis chain, thus introducing filters between the generation and simulation steps. The effect of pile-up from multiple interactions in the same and neighbouring bunch crossings is included in the simulation by overlaying minimum bias events, simulated using PYTHIA 8 with the A2 parameter tune [101] and the MSTW2008LO PDFs [102]. All simulated samples are then passed through the ATLAS reconstruction software. Weights typically close to one are applied to the generated events to account for data/MC differences in the trigger and offline selection efficiencies of leptons, jets, E_T^{miss} , b -jets (such as the b -tagging efficiency scale factors measured in the previous chapter), as well as for data/MC differences in the distribution of the number of pile-up collisions.

Table 6.1 – Monte Carlo samples used for the signal processes and the cross section times branching ratios (BR) used to normalise the different processes at $\sqrt{s} = 13$ TeV. Branching ratios correspond to the decays shown in the first column. Here ℓ is inclusive of e , μ , τ leptons.

Process	Generator (PDF set)	$\sigma \times BR$ [fb]	N_{events}
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	POWHEG v2 + MiNLO + PYTHIA 8 (PDF4LHC15)	89.08	2×10^6
$qq \rightarrow W^+ H \rightarrow \ell^+ \nu b\bar{b}$	POWHEG v2 + MiNLO + PYTHIA 8 (PDF4LHC15)	164.6	1×10^6
$qq \rightarrow W^- H \rightarrow \ell^- \nu b\bar{b}$	POWHEG v2 + MiNLO + PYTHIA 8 (PDF4LHC15)	104.5	2×10^6
$qq \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	POWHEG v2 + MiNLO + PYTHIA 8 (PDF4LHC15)	44.84	3×10^6
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	POWHEG v2 + PYTHIA 8 (PDF4LHC15)	14.30	3.8×10^5
$gg \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	POWHEG v2 + PYTHIA 8 (PDF4LHC15)	7.228	7×10^5

The simulated VH , $H \rightarrow b\bar{b}$ signal samples are summarised in Table 6.1. Events from $qq \rightarrow VH$ plus zero or one jet are generated at next-to-leading order (NLO) in the strong coupling constant using the POWHEG-BOX v2 + MiNLO event generator [79, 103, 104, 105] and the PDF4LHC15_NLO_30_PDFAS [106] PDF set. Electroweak corrections obtained with the HAWK generator [107, 108] are applied as a function of the vector boson transverse momentum. Gluon induced $gg \rightarrow ZH$ events are generated at leading order (LO) using POWHEG-BOX v2. The generators are interfaced to PYTHIA 8 with the AZNLO tune for the modelling of the parton shower (which can produce extra jet radiation), hadronisation and the underlying event.

The samples are produced assuming a Higgs boson mass of 125 GeV and are normalised to the best available theoretical predictions for the VH cross section and $H \rightarrow b\bar{b}$ branching ratio for such a mass, as compiled in Refs. [26, 27, 28, 29]. WH signal samples are normalised to the production cross section calculated at NNLO in α_s and NLO in α . $gg \rightarrow ZH$ samples are normalised to the cross section calculated at NLO in QCD, including next-to-leading logarithm (NLL) corrections. $qq \rightarrow ZH$ signal samples are normalised to the difference between the inclusive ZH cross section, which is calculated at NNLO in QCD with NLO EW corrections, and the $gg \rightarrow ZH$ calculation, to avoid double counting of the gluon-induced contribution.

The simulated background samples used for the analysis are summarised in Table 6.2.

The production of vector bosons in association with jets is generated with SHERPA 2.2.1 using the NNPDF3.0 NNLO PDFs [86] with a dedicated parton shower tuning developed by the SHERPA authors. The matrix elements are calculated at NLO for up to two partons and at LO for up to four partons. In order to generate a sufficient number of events at high p_T^V , several V +jets samples are produced in intervals of the true vector boson transverse momentum. In addition, to generate enough events with heavy-flavour jets, filters are used to produce independent samples enhanced in different flavours of the jets by either requiring one b hadron, or vetoing b hadrons and requiring a c hadron, or vetoing b hadrons and c hadrons. These samples are normalised

Table 6.2 – Monte Carlo samples used for the background processes and the cross section times branching ratios used to normalise the different processes at $\sqrt{s} = 13$ TeV. Branching ratios correspond to the decays shown in the first column. ℓ is inclusive of e, μ, τ leptons.

Process	Generator (PDF set)	$\sigma \times BR$ [pb]	N_{events}
Vector boson + jets			
$Z \rightarrow \nu\nu$	SHERPA 2.2.1 (NNPDF3.0NNLO)	1914	146×10^6
$W \rightarrow \ell\nu$	SHERPA 2.2.1 (NNPDF3.0NNLO)	20080	410×10^6
$Z\gamma^* \rightarrow \ell\ell$	SHERPA 2.2.1 (NNPDF3.0NNLO)	2107 ($m_{\ell\ell} > 40$ GeV)	171×10^6
Top-quark			
$t\bar{t}$	POWHEG v2 + PYTHIA 8 (NNPDF3.0NNLO)	831.76	60×10^6
t, s -channel	POWHEG v1 + PYTHIA 6 (CT10)	3.31	2×10^6
t, t -channel	POWHEG v1 + PYTHIA 6 (CT10)	66.51	10×10^6
t, Wt -channel	POWHEG v1 + PYTHIA 6 (CT10)	68.00	10×10^6
Diboson			
WW	SHERPA 2.2.1 (CT10)	49.74	14.4×10^6
WZ	SHERPA 2.2.1 (NNPDF3.0NNLO)	21.65	28.6×10^6
ZZ	SHERPA 2.2.1 (NNPDF3.0NNLO)	6.53	10.8×10^6

using cross sections calculated at NNLO accuracy in QCD [88]. The V +jets simulated events are classified according to the true flavour of the dijet pair used to reconstruct the Higgs boson candidate as $V + b\bar{b}$, $V + b\bar{c}$, $V + c\bar{c}$, $V + b\bar{l}$, $V + c\bar{l}$, $V + l\bar{l}$ (l =light, either from light quarks u, d, s , or from gluons g). The true flavour of a jet is determined as b, c or l as described in the previous chapter. V +jets events in which at least one of the two jets used to reconstruct the Higgs boson candidate is a b -jet, or both are c -jets (*i.e.* $V + b\bar{b}$, $V + b\bar{c}$, $V + c\bar{c}$, $V + b\bar{l}$), are called in the following the V +heavy flavour (V +HF) background. Most of the events (70–90%) in the V +HF background surviving the selection are from $V + b\bar{b}$.

Top-quark pair events are generated using POWHEG-BOX v2 [109] and the NNPDF 3.0 NNLO PDF set. The generator is interfaced to PYTHIA 8 with the A14 tune [87] for the modelling of parton shower, hadronisation and underlying event. The sample is normalised to the theoretical cross section calculated at NNLO+NNLL [83].

Single top quark events (t, s and Wt channels) are generated using POWHEG-BOX v1 [110, 111] with the CT10 PDF set. The generator is interfaced with PYTHIA 6 using the CTEQ6L1 PDFs [112] for the modelling of parton shower, hadronisation and underlying event. The single-top quark samples are normalised using cross sections calculated at NLO in QCD [113, 114, 115]. In all these samples the top quark mass is set to 172.5 GeV. A filter requires at least one of the W bosons to decay leptonically in events that are passed to the detector simulation.

Diboson samples are generated using SHERPA 2.2.1 and the NNPDF 3.0 NNLO PDFs (WZ, ZZ) or the CT10 PDFs (WW). The matrix elements are calculated at NLO for the real emission of up to one additional parton and at LO for the real emission of up to three additional partons. The inclusive NLO cross-section from Sherpa is used to normalise the events.

To estimate modelling systematic uncertainties, samples are produced with alternative event generators or with alternative settings of the nominal generators, as described in Section 6.8.

6.4 Event selection

The event selection includes a part common to all the three final states, which is based on the properties of the Higgs boson decay products, and specific requirements that are different for each leptonic decay of the vector boson V . The selection is described in detail in the following subsections and summarized in Table 6.3. In the following, the reconstructed transverse momentum $p_T(V)$ of the weak gauge boson produced with the Higgs boson signal is computed as follows: in the 0-lepton channel, $p_T(Z)$ is the total missing transverse energy, E_T^{miss} ; in the 1-lepton channel, p_T^W is the magnitude of the vector sum of the transverse missing momentum vector and of the lepton transverse momentum vector; in the 2-lepton channel, $p_T(Z)$ is computed from the sum of the transverse momentum vectors of the two leptons.

Table 6.3 – Summary of the event selection in the 0-, 1- and 2-lepton channels.

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\text{T}}^{\text{miss}}$	Single lepton	$E_{\text{T}}^{\text{miss}}$	Single lepton
Leptons	0 VH -loose leptons with $p_{\text{T}} > 7$ GeV	1 VH -signal electron $p_{\text{T}} > 27$ GeV	1 VH -signal muon $p_{\text{T}} > 25$ GeV	2 VH -loose leptons with $p_{\text{T}} > 7$ GeV ≥ 1 lepton with $p_{\text{T}} > 27$ GeV
$E_{\text{T}}^{\text{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV for $ \eta < 2.5$ and > 30 GeV for $2.5 < \eta < 4.5$			
b -jets	Exactly 2 b -tagged jets			
Leading b -tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), > 150 GeV (3 jets)	–	–	–
$\min[\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, \text{jets})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–	–	–
$\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, b\bar{b})$	$> 120^\circ$	–	–	–
$\Delta\phi(b_1, b_2)$	$< 140^\circ$	–	–	–
$\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, \mathbf{E}_{\text{T, trk}}^{\text{miss}})$	$< 90^\circ$	–	–	–
p_{T}^V	> 150 GeV			> 75 GeV
Signal regions	✓	$m_{b\bar{b}} \geq 75$ GeV or $m_{\text{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{b\bar{b}} < 75$ GeV and $m_{\text{top}} > 225$ GeV		Different-flavour leptons

The acceptance of the selection criteria for the VH signal, together with the predicted cross sections times $H \rightarrow b\bar{b}$ branching ratios, are shown in Table 6.4. The acceptance for gluon-induced ZH events is larger than for quark-induced ones because the p_T^V spectrum is larger, leading to larger acceptance and reconstruction efficiencies of the charged leptons ($Z \rightarrow \ell\ell$) or of the missing transverse energy ($Z \rightarrow \nu\nu$).

Table 6.4 – The VH signal cross-section times branching ratio and acceptance in the three channels at $\sqrt{s} = 13$ TeV. The qq - and gg -initiated ZH processes are shown separately. The branching ratios are calculated considering only decays to muons and electrons for $Z \rightarrow \ell\ell$, decays to all three lepton flavours for $W \rightarrow \ell\nu$ and decays to all neutrino flavours for $Z \rightarrow \nu\nu$. The acceptance is calculated as the fraction of events remaining in the combined signal and control regions after the full event selection.

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	$\sigma \times BR$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	29.9	< 0.1	< 0.1	7.0
$gg \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	4.8	< 0.1	< 0.1	15.7
$qq \rightarrow WH \rightarrow \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	14.3	3.5	–	–

6.4.1 Common event selection

The reconstruction of the primary vertices, of the hard-scatter vertex candidate, and of the various particles is described in chapter 4. The following overlap-removal procedure is applied to avoid the case of the same particle being reconstructed as two different candidates. Hadronically decaying τ lepton candidates within $\Delta R = 0.2$ of an electron or muon of good quality are removed. Electrons sharing the same track with muons are removed. Jets in a cone of $\Delta R = 0.2$ around an electron are removed. Jets in a cone of $\Delta R = 0.2$ around a muon, with less than three associated tracks or with energy close to that of the muon, are removed. Electrons and muons, typically from semileptonic b or c -hadron decays, that are within a cone of radius equal to the minimum between 0.4 and $10 \text{ GeV}/p_T$ around the remaining jets are removed. Finally, jets in a cone of $\Delta R = 0.2$ around hadronically decaying τ lepton candidates are removed.

The selection requirements applied to the leptons used for this analysis are summarised in Tables 6.5 and 6.6. Two different level of selections are defined to select the leptons in the final state under study or to veto extra leptons: a “ VH ”-loose selection and a “ WH ”- or “ ZH ”-signal one. The VH -signal selections apply tighter transverse momentum thresholds and identification and isolation requirements than the VH -loose one. Requirements on the significance of the transverse impact parameter d_0 and on the longitudinal impact parameter z_0 with respect to the hard-scatter vertex are applied to both loose and signal leptons to reject non-prompt and pile-up tracks.

The isolation selection for VH -loose electrons requires them to be isolated from other tracks reconstructed in the ID in a cone with ΔR varying with p_T (maximum $\Delta R = 0.2$). The requirement is tuned to give a 99% constant efficiency as a function of the electron p_T . Signal electrons

must also pass a tighter calorimeter-based isolation selection requiring the sum of the transverse energy of the clusters of calorimeter cells not associated to the electron and within $\Delta R = 0.2$ of the electron to be below 3.5 GeV.

The VH -loose muons are required to be isolated from tracks in the ID in a cone with ΔR varying with p_T (maximum $\Delta R = 0.3$). The requirement is tuned to give a 99% constant efficiency as a function of the muon p_T . VH -signal muons are required to pass the tighter track-based isolation requirement that the scalar sum of the p_T of the tracks in a cone of $\Delta R = 0.2$ around the muon be below 1.25 GeV.

Also for the jets two sets of quality criteria are defined for this analysis, as summarised in Table 6.7. “Signal” jets are required to be central ($|\eta| < 2.5$), to have $p_T > 20$ GeV, and to pass a JVT requirement in order to suppress pile-up jets. “Forward” jets are those in the $2.5 < |\eta| < 4.5$ pseudorapidity region, which is not covered by the ID. To suppress pile-up forward jets, since there is no JVT discriminant for them, their minimum p_T threshold is raised to 30 GeV.

Table 6.5 – Electron selection requirements.

Electron category	p_T	η	ID	d_0^{sig} w.r.t. PV	$ \Delta z_0 \sin \theta $	Isolation
VH -loose	>7 GeV	$ \eta < 2.47$	Loose + hit in IBL	< 5	< 0.5 mm	loose (only tracks)
ZH -signal	>27 GeV	$ \eta < 2.47$	Loose + hit in IBL	< 5	< 0.5 mm	loose (only tracks)
WH -signal	>27 GeV	$ \eta < 2.47$	Tight	< 5	< 0.5 mm	tight (tracks+calorimeter)

Table 6.6 – Muon selection requirements.

Muon category	p_T	η	ID	d_0^{sig} w.r.t. PV	$ \Delta z_0 \sin \theta $	Isolation
VH -loose	>7 GeV	$ \eta < 2.7$	Loose	< 3	< 0.5 mm	loose (only tracks)
ZH -signal	>27 GeV	$ \eta < 2.5$	Loose	< 3	< 0.5 mm	loose (only tracks)
WH -signal	>25 GeV	$ \eta < 2.5$	Medium	< 3	< 0.5 mm	tight (only tracks)

Table 6.7 – Jet selection requirements.

Jet category	Selection Requirements
Signal Jets	$p_T > 20$ GeV
	$ \eta < 2.5$
	$\text{JVT} \geq 0.59$ if ($p_T < 60$ GeV and $ \eta < 2.4$)
Forward Jets	$p_T > 30$ GeV
	$2.5 \leq \eta < 4.5$

Jets from the hadronisation of the b -quarks from the Higgs boson decay in VH events tend to be produced at small pseudorapidity; moreover, b -tagging can only be performed for jets in the ID acceptance ($|\eta| < 2.5$). For this reason only the “signal jets” are used to select the $H \rightarrow b\bar{b}$ candidates. To this purpose they must be identified as containing b hadrons by the MV2c10 algorithm described in the previous chapter. The MV2c10 working point, chosen to maximise the expected signal significance, is the one with a fixed threshold yielding a nominal average efficiency of 70% on b -jets and misidentification efficiencies of 8.2% and 0.3% for c -jets and light-flavour jets, for jets with $p_T > 20$ GeV and $|\eta| < 2.5$ produced in $t\bar{t}$ events.

All events are required to have at least two jets, and exactly two must pass the b -tagging requirement. These two jets are then used to form the Higgs boson candidate. Since Higgs boson decays tend to produce at least one b -jet with p_T above a few tens of GeV, a requirement $p_T > 45$ GeV is applied to the leading- p_T jet to improve the signal-to-background ratio.

The momentum of the reconstructed b -jet candidates is corrected to improve the accuracy of the standard jet energy calibration (which is derived with data control samples enriched in light-flavoured jets). The following two effects are taken into account:

- First of all, when a muon with $p_T > 5$ GeV and of medium quality is found in a cone of size $\Delta R = 0.4$ around the jet, the muon four-momentum is added to that of the jet, and the energy deposited in the calorimeter by the muon is removed from the jet energy. This “muon-in-jet” correction accounts for muons from semileptonic decays of b - or c -hadrons and for the fact that the muon momentum is better measured by the tracking devices than by the calorimeter. No isolation requirement is applied to the muon. Taking into account that $BR(W \rightarrow \mu\nu) + BR(W \rightarrow \tau\nu, \tau \rightarrow \mu\nu\nu) = 12\%$ and that there are two W bosons in the $b \rightarrow c \rightarrow d, s$ decay chain, the probability per b -jet to contain at least a muon is about 24%, and thus the probability of two b -jet events to receive such a correction is about 42%. If there is more than one muon satisfying such requirements (which happens in 1.6% of the cases in the simulation) only the closest one to the jet is used.
- Second, a “PtReco” correction is applied as a function of the jet transverse momentum and is computed as the average relative difference between the calibrated energy of the reconstructed b -jet and the true b -jet energy, as determined from the simulation. The correction is determined separately for jets in which the b -hadron decay chain produces only hadrons (“hadronic jets”) or also leptons and neutrinos (“semileptonic jets”). As illustrated in Figure 6.1, the PtReco correction for “hadronic” jets increases the jet energy by around 12% for a jet p_T of 20 GeV and by around 1% above 100 GeV, while for “semileptonic” jets the correction factors are about 10% larger to account for the neutrino momentum.

For 2-lepton events the PtReco correction is replaced by a kinematic likelihood fit which includes a constraint on the dilepton invariant mass (Breit-Wigner distribution with the Z boson parameters), constraints on each of the transverse components of the $\ell\ell b\bar{b}$ system momentum (Gaussian distributions centered at zero with a width of 9 GeV, as obtained from ZH simulated events), a prior distribution of the true jet p_T in ZH events, and a transfer function relating the reconstructed jet p_T to its true value.

The effect of these corrections on the invariant mass distribution of simulated $ZH \rightarrow \ell\ell b\bar{b}$ signal events passing the 2-lepton selection and having $p_T^Z > 150$ GeV is shown in Figure 6.2. The muon-in-jet and PtReco corrections lead to a resolution improvement close to 20% with respect to the standard calibration; the kinematic fit doubles the gain to slightly more than 40%.

In the 0-lepton channel, background from $t\bar{t}$ events arise typically from $qqb\ell\nu b$ events (*i.e.* one W boson decays hadronically and the other one leptonically)¹ where one lepton is not

¹ $qqbqqb$ events (*i.e.* both W bosons decay hadronically) with large fake missing transverse momentum are suppressed by the large E_T^{miss} requirement applied, as described later.

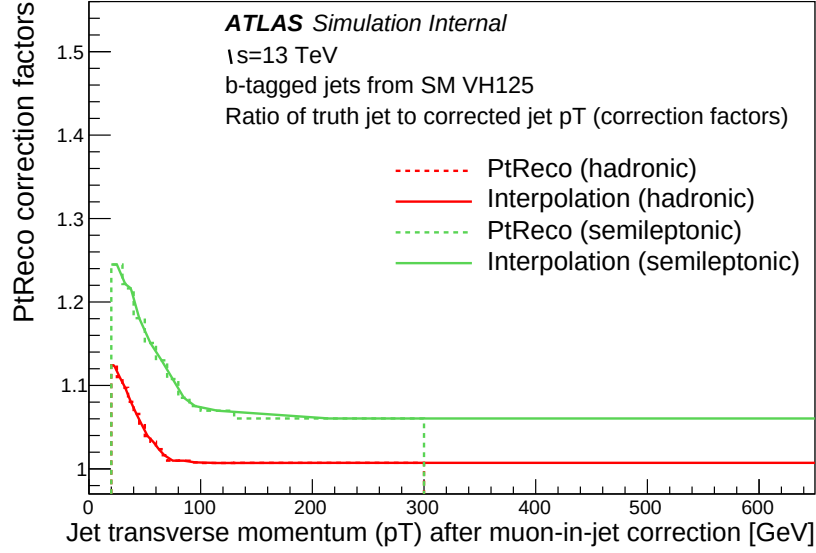


Figure 6.1 – “PtReco” jet energy correction as a function of jet p_T , for both semileptonic and hadronic decays of the b hadrons inside the b -jets, obtained from simulated VH , $H \rightarrow b\bar{b}$ samples.

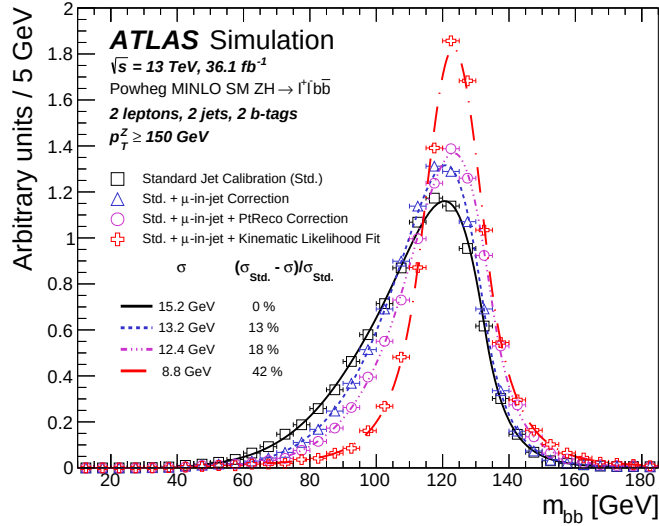


Figure 6.2 – Comparison of the m_{bb} distributions as additional corrections are applied to the jet energy scale, for simulated signal events in the 2-lepton channel in the 2-jet, $p_T^Z > 150$ GeV region.

reconstructed. Such events have typically at least four jets in the event. Similarly, in the 1-lepton channel, $t\bar{t}$ background events are dominated by the $q\bar{q}b\ell\nu b$ final state. To reduce $t\bar{t}$ contamination the number of jets is thus required to be at most three. In the 2-lepton channel, both the signal and the backgrounds (including $t\bar{t}$, which contributes mostly through the $\ell\nu b\ell\nu b$ final state) have low jet multiplicity, and a maximum N_{jet} requirement does not improve S/B . For this channel, also events with more than three jets are thus considered, increasing the sensitivity (by about 5–6%) due to the slightly larger acceptance for the signal.

6.4.2 0-lepton channel specific selection

The 0-lepton channel targets mainly ZH events with Z bosons decaying to neutrinos. Events are recorded using $E_{\text{T}}^{\text{miss}}$ triggers. In the offline analysis events are required to have no VH -loose leptons and $E_{\text{T}}^{\text{miss}} > 150$ GeV. To remove a small region of phase space in which the trigger efficiency exhibits a dependence on the jet multiplicity not well modelled in the data, a selection is applied to the scalar sum H_{T} of the transverse momenta of the jets in the event. Two-jet (three-jet) events are required to have $H_{\text{T}} > 120$ (150) GeV.

To suppress multi-jet background, mostly originating from jets poorly reconstructed in the calorimeters, a selection on some variables exploiting the angular correlations of various particles either in signal or background events is applied. The requirements are the following:

- $\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, \mathbf{E}_{\text{T, trk}}^{\text{miss}}) < 90^\circ$,
- $\Delta\phi(\mathbf{b}_1, \mathbf{b}_2) < 140^\circ$,
- $\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, \mathbf{bb}) > 120^\circ$,
- $\min[\Delta\phi(\mathbf{E}_{\text{T}}^{\text{miss}}, \mathbf{jets})] > 20^\circ$ for 2 jets $> 30^\circ$ for 3 jets.

Here $\mathbf{E}_{\text{T}}^{\text{miss}}$ and $\mathbf{E}_{\text{T, trk}}^{\text{miss}}$ indicate the missing transverse momentum vectors calculated using calorimeter or tracking information (the latter is also sometimes denoted $\mathbf{p}_{\text{T}}^{\text{miss}}$ elsewhere); $\mathbf{b}_1$ and $\mathbf{b}_2$ are the directions of the two b -tagged jets, and $\mathbf{bb}$ is the direction of the two-body system formed by the two b -tagged jets. $\Delta\phi(\mathbf{a}, \mathbf{b})$ is the azimuthal angle between two vectors $\mathbf{a}$ and $\mathbf{b}$. The first requirement exploits the fact that for events with real transverse momentum imbalance (such as the signal), its reconstructed direction should be similar when using calorimeter or tracking information, while in multi-jet events with jets poorly reconstructed in the calorimeter and low true momentum imbalance the direction of $\mathbf{E}_{\text{T}}^{\text{miss}}$ and $\mathbf{E}_{\text{T, trk}}^{\text{miss}}$ should be largely uncorrelated. The second requirement accounts for the fact that the b -jets from the decay of a 125 GeV Higgs boson recoiling against a high- p_{T} V boson tend (due to the boost of the system) to be close in space, more than – on average – random jets in low-multiplicity QCD events. The third requirement accounts for the fact that in signal events the directions of $\mathbf{E}_{\text{T}}^{\text{miss}}$ and of the bb system are close to those of the Z and Higgs bosons, which should be mostly back-to-back in the transverse plane. The final selection suppresses QCD multi-jet events since fake $E_{\text{T}}^{\text{miss}}$ is usually due to a poor energy reconstruction of one jet which implies that $\mathbf{E}_{\text{T}}^{\text{miss}}$ tends to be aligned with the direction of the misreconstructed jet. The previous criteria have been chosen in such a way that the fraction of multi-jet contamination is on the order of 1% of the total background and on the order of 10% of the signal in a narrow bb invariant mass window around 125 GeV.

6.4.3 1-lepton channel specific selection

The 1-lepton channel targets mainly WH events with a W boson decaying to a charged lepton and a neutrino.

In the 1-electron sub-channel, events are recorded using single-electron triggers. Events are required to contain exactly one WH -signal electron and no additional VH -loose leptons. The selected electron is required to have triggered the acquisition of the event.

In the 1-muon sub-channel, events are recorded using the E_T^{miss} triggers. Events are required to contain exactly one WH -signal muon and no additional VH -loose leptons.

In both sub-channels, the transverse momentum of the W boson candidate, defined as the magnitude of the vector sum of the lepton and E_T^{miss} directions in the transverse plane, must be larger than 150 GeV. Such requirement suppresses multi-jet contamination due to events with jets faking prompt leptons. In the electron sub-channel, to reduce multi-jet contamination further, E_T^{miss} is required to be larger than 30 GeV.

To better estimate the $W + \text{HF}$ background from the data, the selected sample is split into a signal region (SR) and a dedicated $W + \text{HF}$ control region (CR). The $W + \text{HF}$ control region is defined by applying, on top of the previous selection criteria, the following requirements:

- $m_{bb} < 75$ GeV, to suppress signal and diboson contributions;
- $m_{\text{top}} > 225$ GeV, to suppress $t\bar{t}$ and single-top-quark events.

The quantity m_{top} is the reconstructed mass of the top quark assumed to be decaying to one of the two b -jet candidates and the W boson that has then decayed to the selected lepton. The calculation of m_{top} uses the four-momenta of one of the two b -jet candidates, the signal lepton, and of the hypothetical neutrino produced in the event. The transverse momentum of the neutrino is assumed to be equal to the missing transverse momentum vector, while its longitudinal momentum is determined from the lepton momentum and the missing transverse momentum vector assuming that they originate from the decay of a particle (the W boson) with known mass $m_W = 81$ GeV:

$$p_z^\nu = \frac{1}{2(p_T^l)^2} \left[p_z^l X \pm E_l \sqrt{X^2 - 4(p_T^l)^2 (E_T^{\text{miss}})^2} \right], \quad (6.1)$$

where

$$X = m_W^2 + 2p_x^l E_x^{\text{miss}} + 2p_y^l E_y^{\text{miss}}. \quad (6.2)$$

If the previous quadratic equation has imaginary solutions, the magnitude of E_T^{miss} is increased until the discriminant in the quadratic equation is equal to zero. m_{top} is then reconstructed from the combination of b -jet candidate and p_z^ν that yields a top quark candidate mass closest to the nominal value of 172.5 GeV. The fraction of $W + \text{HF}$ events in the $W + \text{HF}$ control sample expected from the simulation is around 75%.

6.4.4 2-lepton channel specific selection

The 2-lepton channel targets mainly ZH events with the Z boson decaying to a pair of same flavour leptons (ee or $\mu\mu$).

Events are recorded using single-electron or single-muon triggers. Exactly two VH -loose leptons of the same flavour are required. One of the two leptons is required to have $p_T > 27$ GeV (ZH -signal lepton) and to have triggered the acquisition of the event.

The charges of the two leptons are required to be opposite in muon sub-channel. A similar requirement is not applied in the electron sub-channel due to the non-negligible charge misidentification rate of electrons.

The invariant mass of the two leptons must be sufficiently close to the Z boson pole mass, $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$, reducing contributions from $t\bar{t}$ and multi-jet events that produce non-resonant lepton pairs.

Finally, the transverse momentum of the dilepton pair, which for signal events originates from the Z boson recoiling against the Higgs boson, is required to be larger than 75 GeV.

To better estimate the $t\bar{t}$ and Wt background from the data, a dedicated top control region is defined, applying the nominal 2-lepton selection with the exception of the same-flavour requirement, which is replaced by the requirement that the two leptons have different flavour (*i.e.* selecting $e\mu$ combinations), with no criteria applied to their charges. The different-flavour request strongly suppresses processes with real Z bosons (Z +jet, diboson, Higgs boson production) and thus the top control region is 99% pure in $t\bar{t} + Wt$ events. At the same time, since the kinematic properties of top-quark events are flavour symmetric, the selected control sample is highly representative of top-quark background events in the 2-lepton signal region, as shown in Figure 6.3.

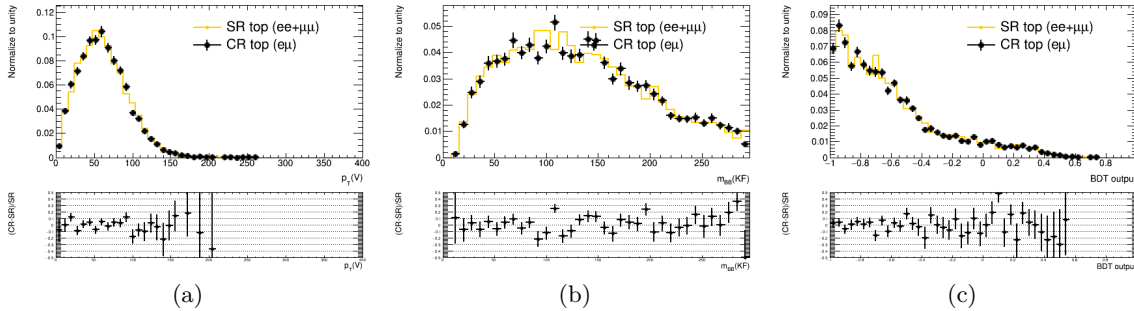


Figure 6.3 – Shape comparison between top background distributions in the same flavor signal region and in the different-flavor top control region in 2-jet low- $p_T(V)$ region: (a) $p_T(V)$, (b) bb invariant mass, (c) BDT_{VH} . Both shapes are normalised to unity.

6.5 Event classification

The extraction of the signal and background yields in the selected sample is performed separately in event categories with different S/B , to increase the sensitivity of the analysis.

The events are classified based on:

- the number of charged leptons N_{lepton} : 0, 1, or 2. Electron and muon sub-channels are combined together and not treated separately in the 1-lepton and 2-lepton channels.
- the number of jets in the event, N_{jet} . For each N_{lepton} category, selected events are classified into 2-jet events and events with 3 jets (or at least 3 jets in the 2-lepton channel).

- the transverse momentum of the vector boson, $p_T(V)$. In the 2-lepton channel, events are classified in two categories, events with “medium” $p_T(V)$, $75 \text{ GeV} < p_T(V) < 150 \text{ GeV}$, and events with “high” $p_T(V)$, $p_T(V) > 150 \text{ GeV}$. No $p_T(V)$ categories are introduced for the 0-lepton and 1-lepton channels.

The total number of signal regions is thus 8: events that pass the nominal selection and are classified in one of the following categories:

- 0 leptons, 2 jets or 3 jets;
- 1 lepton, 2 jets or 3 jets;
- 2 leptons, 2 jets or ≥ 3 jets, $75 \text{ GeV} < p_T(V) < 150 \text{ GeV}$;
- 2 leptons, 2 jets or ≥ 3 jets, $p_T(V) > 150 \text{ GeV}$.

There are also six control regions:

- two W +HF control regions, corresponding to events passing the 1-lepton W +HF selection, either with 2 jets or 3 jets;
- four top control regions, corresponding to events passing the 2-lepton top control sample selection, with 2 jets or ≥ 3 jets, and $75 \text{ GeV} < p_T(V) < 150 \text{ GeV}$ or $p_T(V) > 150 \text{ GeV}$.

6.6 Multivariate analysis

In the nominal measurement, the signal and background yields are determined by means of a simultaneous maximum-likelihood fit to the distribution, in each of the selected signal regions, of a multivariate discriminant combining into a single output the values of several correlated kinematic quantities. The expected signal and background distributions are determined from the simulation. The normalisations of the various background processes are determined from the theoretical cross section calculations and the efficiencies predicted by the simulation, or directly from the data. In particular, the multivariate algorithm that is used is a boosted decision tree, in the implementation provided by the TMVA package [95]. To better constrain the top and W +HF backgrounds, the $b\bar{b}$ invariant mass distribution or the number of events in the control regions are fitted simultaneously with the fits to the BDT distributions of the eight signal regions. The different regions entering the likelihood fit and the discriminant used in each region are summarised in Table 6.8.

Two sets of BDTs are used. One, denoted as BDT_{VH} , aims at separating the VH , $H \rightarrow b\bar{b}$ signal from all the backgrounds, and is used in the nominal analysis. The other one, denoted as BDT_{VZ} , aims at separating VZ , $Z \rightarrow b\bar{b}$ events from the other background processes and the VH signal; such BDT is used in the diboson analysis cross-check. Both BDTs use the same

Table 6.8 – The distributions used in the global likelihood fit for the signal regions (SR) and control regions (CR) for all the categories in each channel, for the nominal multivariate analysis.

Channel	SR/CR	Categories			
		$75 \text{ GeV} < p_T^V < 150 \text{ GeV}$		$p_T^V > 150 \text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	$W + \text{HF CR}$	-	-	Yield	Yield
2-lepton	$e\mu \text{ CR}$	m_{bb}	m_{bb}	Yield	m_{bb}

set of input variables, which describe the event kinematics and topology. The input variables have been chosen to maximise the sensitivity of the analysis, using the following procedure. Starting from the invariant mass of the two b -jets (m_{bb}), variables are added one at a time to the BDT, and the one that gives the best increase in separation between signal and background is kept. The procedure continues until no more variables are found that give a non-negligible improvement in the signal-vs-background separation. The list of input variables retained after the application of this procedure is shown in Table 6.9.

The input variables are defined as follows:

Table 6.9 – Variables used for the multivariate discriminant in each of the categories.

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{\text{miss}}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\mathbf{b}_1, \mathbf{b}_2)$	$\times$	$\times$	$\times$
$ \Delta\eta(\mathbf{b}_1, \mathbf{b}_2) $	$\times$		
$\Delta\phi(\mathbf{V}, \mathbf{bb})$	$\times$	$\times$	$\times$
$ \Delta\eta(\mathbf{V}, \mathbf{bb}) $			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\ell, \mathbf{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
m_{top}		$\times$	
$ \Delta y(\mathbf{V}, \mathbf{bb}) $		$\times$	
Only in 3-jet events			
$p_T^{\text{jet}_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

- $E_{\text{T}}^{\text{miss}}$: missing transverse momentum;
- p_{T}^V : transverse momentum of the vector boson;
- $p_{\text{T}}^{b_{1,2}}$: transverse momenta of the two b -tagged jets, which are labelled as b_1 and b_2 in order of decreasing p_{T} ;
- $\Delta R(\mathbf{b}_1, \mathbf{b}_2)$: angular separation of the two b -tagged jets;
- $|\Delta\eta(\mathbf{b}_1, \mathbf{b}_2)|$: separation in pseudorapidity of the two b -tagged jets;
- $\Delta\phi(\mathbf{V}, \mathbf{bb})$: azimuthal angle between the vector boson and the system of the two b -tagged jets;
- $|\Delta\eta(\mathbf{V}, \mathbf{bb})|$: pseudorapidity separation between the vector boson and the system of the two b -tagged jets;
- m_{eff} : scalar sum of the transverse momenta of all jets and $E_{\text{T}}^{\text{miss}}$;
- $\min[\Delta\phi(\ell, \mathbf{b})]$: angle between the lepton and the closest b -tagged jet in the transverse plane;
- m_{T}^W : transverse mass of the W boson candidate, defined as $m_{\text{T}}^W = \sqrt{2p_{\text{T}}^\ell E_{\text{T}}^{\text{miss}}(1 - \cos(\Delta\phi(\ell, E_{\text{T}}^{\text{miss}}))}$;
- $m_{\ell\ell}$: invariant mass of the two leptons;
- m_{top} : assuming that the one-lepton selected event is from a semileptonic $t\bar{t}$ event, the reconstructed mass of the top quark candidate decaying leptonically;
- $|\Delta y(\mathbf{V}, \mathbf{bb})|$: the rapidity separation between the W and Higgs boson candidates; it is calculated by reconstructing the neutrino longitudinal momentum using the W boson mass constraint, similarly to m_{top} ;
- $p_{\text{T}}^{\text{jet}_3}$: the transverse momentum of the third jet, which is labelled as jet_3 , in 3-jet events;
- m_{bbj} : the invariant mass of the 3-jet system, in 3-jet events.

As an example, the signal and background input distributions passed to the BDT in the 0-lepton channel are shown in Figure 6.4. The correlation matrices of such variables for signal and background events are shown in Figure 6.5. The distributions and their correlations are different between signal and background, and such properties are exploited by the BDT to maximise the separation between the two kinds of processes. Compared to a simpler cut-based approach in

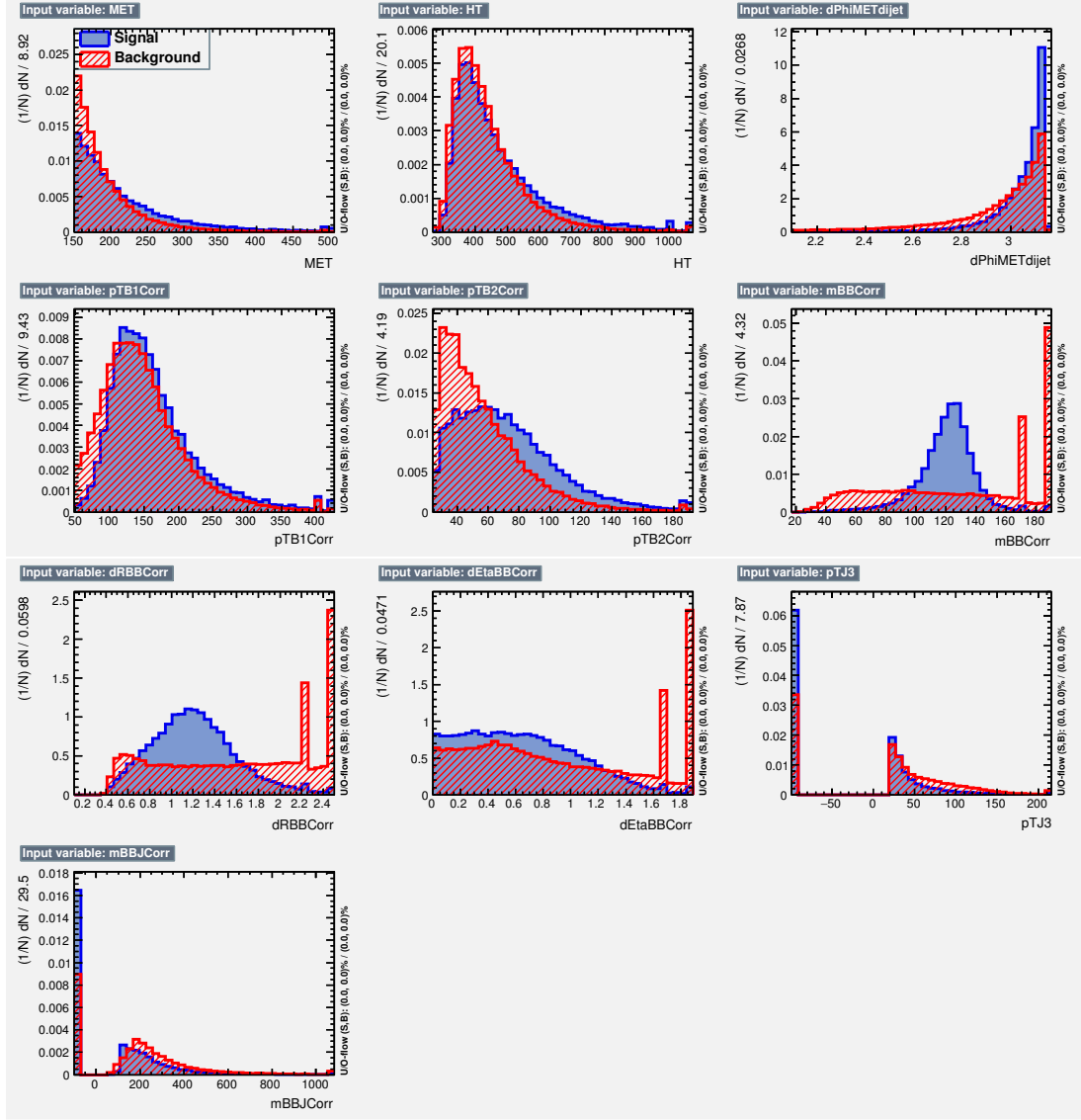


Figure 6.4 – Signal (blue) and background (red) distributions of the BDT input variables in the 0-lepton channel.

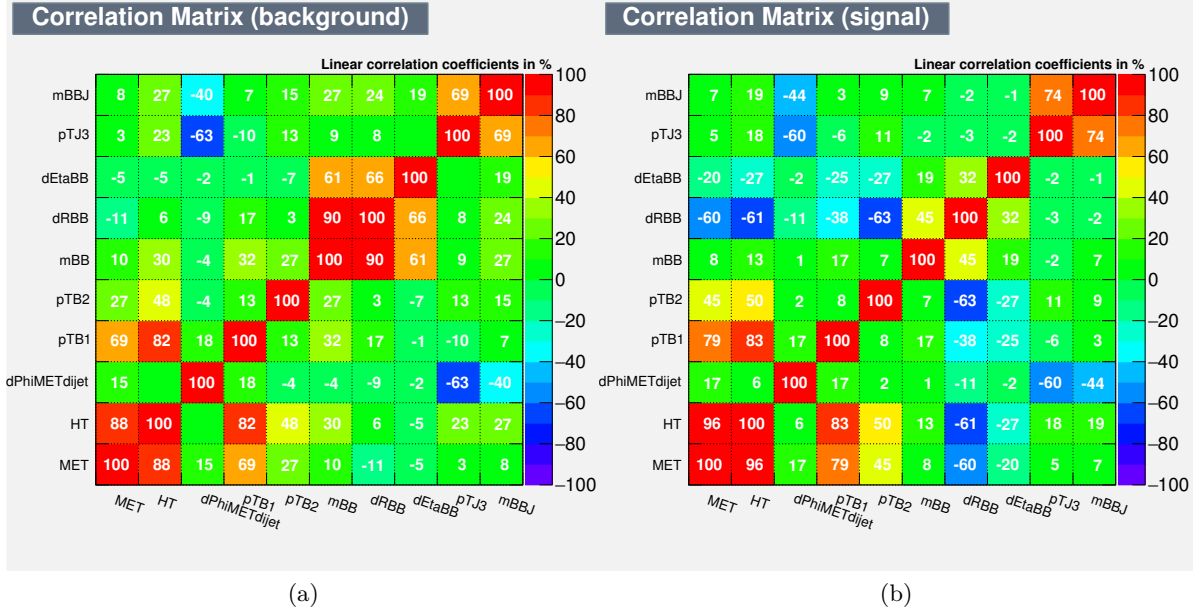


Figure 6.5 – Correlation matrices of the input variables used in the 0-lepton channel BDT for (a) background and (b) signal events.

which a fit to a single kinematic variable like m_{bb} is performed, after having applied selections on the other variables, the use of a multivariate approach provides an increase of the sensitivity of the analysis by about 10%, as will be shown later when comparing the results of the nominal analysis to those of the dijet-mass analysis.

The distributions of the input variables of the BDTs in data and simulation are found to be in good agreement within the uncertainties, as exemplified in Figure 6.6.

The BDTs are trained using simulated signal and background events. Separate BDTs are trained for each signal region. A 2-fold cross-validation strategy is used: one training is performed using even-numbered MC events, and then it is validated on odd-numbered events to estimate its performance on an unbiased sample and to check for overtraining, and viceversa. To exploit the full simulated samples, the distribution of the BDT in half of the data events is computed using the version trained on odd-numbered MC events, and that of the other half is computed using the version trained on even-numbered MC events.

To increase the number of simulated events available in the training, for background processes with large cross section but that are highly suppressed due to the large rejection of light and charm jets by the b -tagging algorithm, a procedure called “parameterised tagging” is used instead of applying the b -tagging algorithm explicitly (“direct tagging”). This procedure relies on a parametrisation of the b -tagging efficiency of light and charm jets as a function of their transverse momentum and pseudorapidity, determined from simulated $t\bar{t}$ events. Such efficiencies are then used to assign a weight to each simulated event, based on the probability that exactly two jets are b -tagged. All simulated events that pass the selection criteria, with the exception of the b -tagging ones, are then used, which reduces significantly the statistical fluctuations for background processes with no b quarks. For this reason this procedure is applied to the $V + cc$, $V + cl$, $V + ll$ and WW samples, which correspond to less than 2% of the total background. Studies have been carried out to determine the impact of possible biases introduced by this procedure. As an example, Figure 6.7 presents comparisons of the m_{bb} distribution when

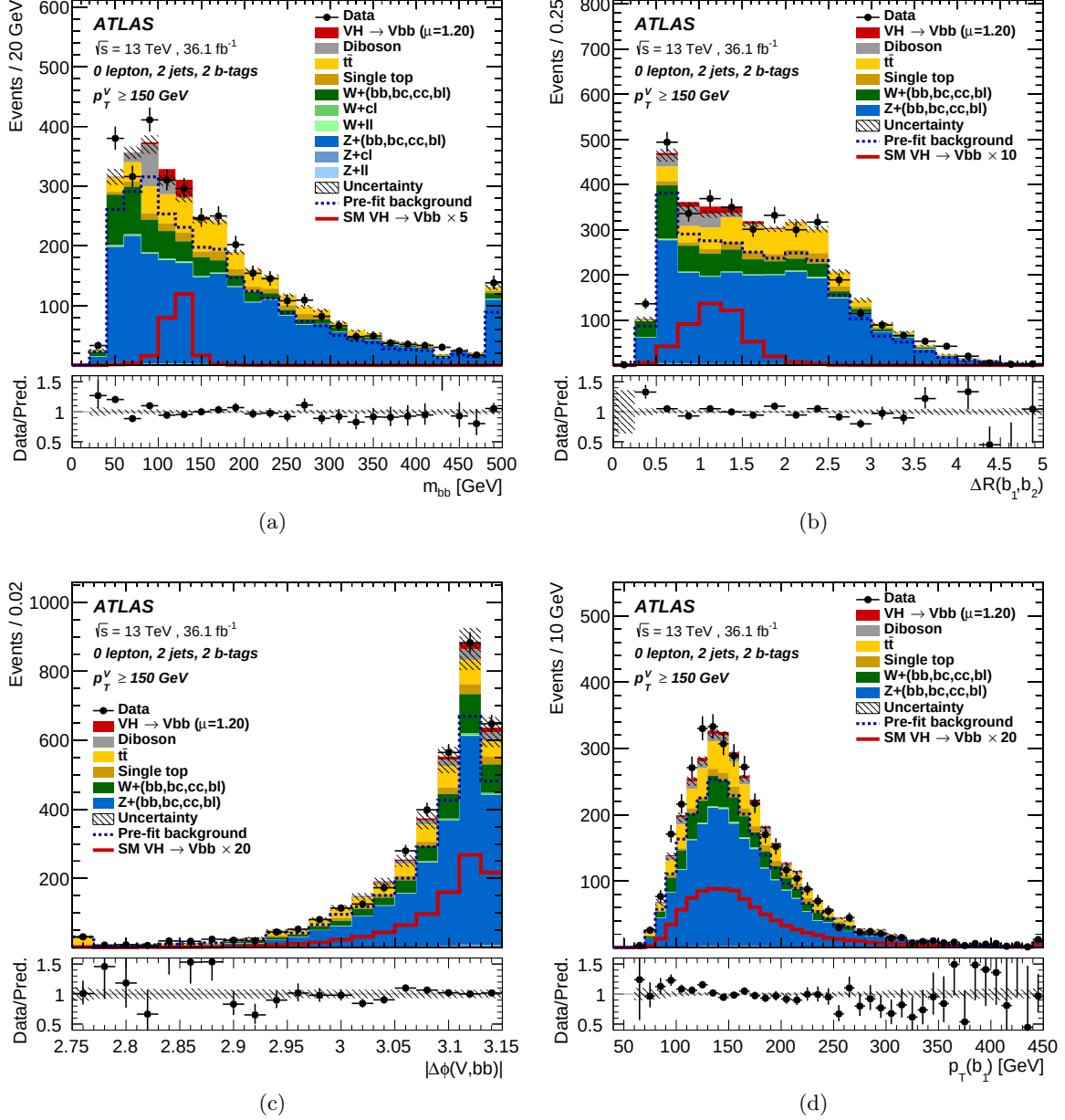


Figure 6.6 – Data vs MC comparison for some of the BDT input variables used in the 0-lepton channel, in the 2-jet signal region: (a) m_{bb} , (b) $\Delta R(b_1, b_2)$, (c) $|\Delta\phi(V, bb)|$, (d) $p_T(b_1)$. Both the signal and background histograms are normalised to the yields determined from the maximum likelihood fit described later. The dashed histogram shows the total background as expected from the pre-fit MC simulation. The entries in overflow are included in the last bins of the histograms. The combined statistical and systematic uncertainty for the sum of the signal and fitted background are indicated by the hatched band. The ratio of the data to the sum of the signal and fitted background is shown in the lower panels.

using direct b -tagging (black points) and parameterised tagging (red points) for $W + cc, cl, ll$ processes in the 1-lepton 2-jet and 3-jet signal regions. As expected, the statistical fluctuations are reduced by parameterised tagging. A reasonably good closure is observed, with possibly a 10–20% disagreement in the $W + cc$ yield between the two approaches; however, given the small contribution of this background process, and its large normalisation uncertainty, the impact of such bias – if any – is minimal.

The parameters used for the training of the BDT were optimised for the VH , $H \rightarrow b\bar{b}$ search with ATLAS Run 1 data by means of one-dimensional “scans” of each of the parameters, in which the BDT was retrained with different values of a particular setting, and the sensitivity of the analysis on simulated samples was compared to some reference value. Checks of a few alternative settings with the samples used in this analysis have indicated that the nominal ones are still optimal, and are summarised in Table 6.10. Signal-like events correspond to BDT output values close to 1, and background-like events have BDT output values close to -1 . The BDT output after the training from TMVA for the 0-lepton channel, and its validation on a statistically independent sample, is shown in Figure 6.8.

Table 6.10 – BDT training settings.

TMVA Setting	Definition	Value
BoostType	Boost procedure	AdaBoost
AdaBoostBeta	Learning rate	0.15
SeparationType	Node separation gain	GiniIndex
PruneMethod	Pruning method	NoPruning
NTrees	Number of trees	200
MaxDepth	Maximum tree depth	4
nCuts	Number of equally spaced cuts tested per variable per node	100
nEventsMin	Minimum number of events in a node	5%

The BDT output histograms from TMVA are re-binned in a way that optimises the sensitivity of the analysis while minimising the number of bins, to reduce statistical fluctuations in the templates determined from the simulation and used in the final fit. The binning procedure is based on the following quantity:

$$Z(I[k, l]) = \frac{z_s n_s(I[k, l])}{N_s} + \frac{z_b n_b(I[k, l])}{N_b}, \quad (6.3)$$

where

- $I[k, l]$ is an interval of the histograms, containing the bins between bin k and bin l ;
- N_s is the total number of signal events in the histogram;
- N_b is the total number of background events in the histogram;
- $n_s(I[k, l])$ is the number of signal events in the interval $I[k, l]$;

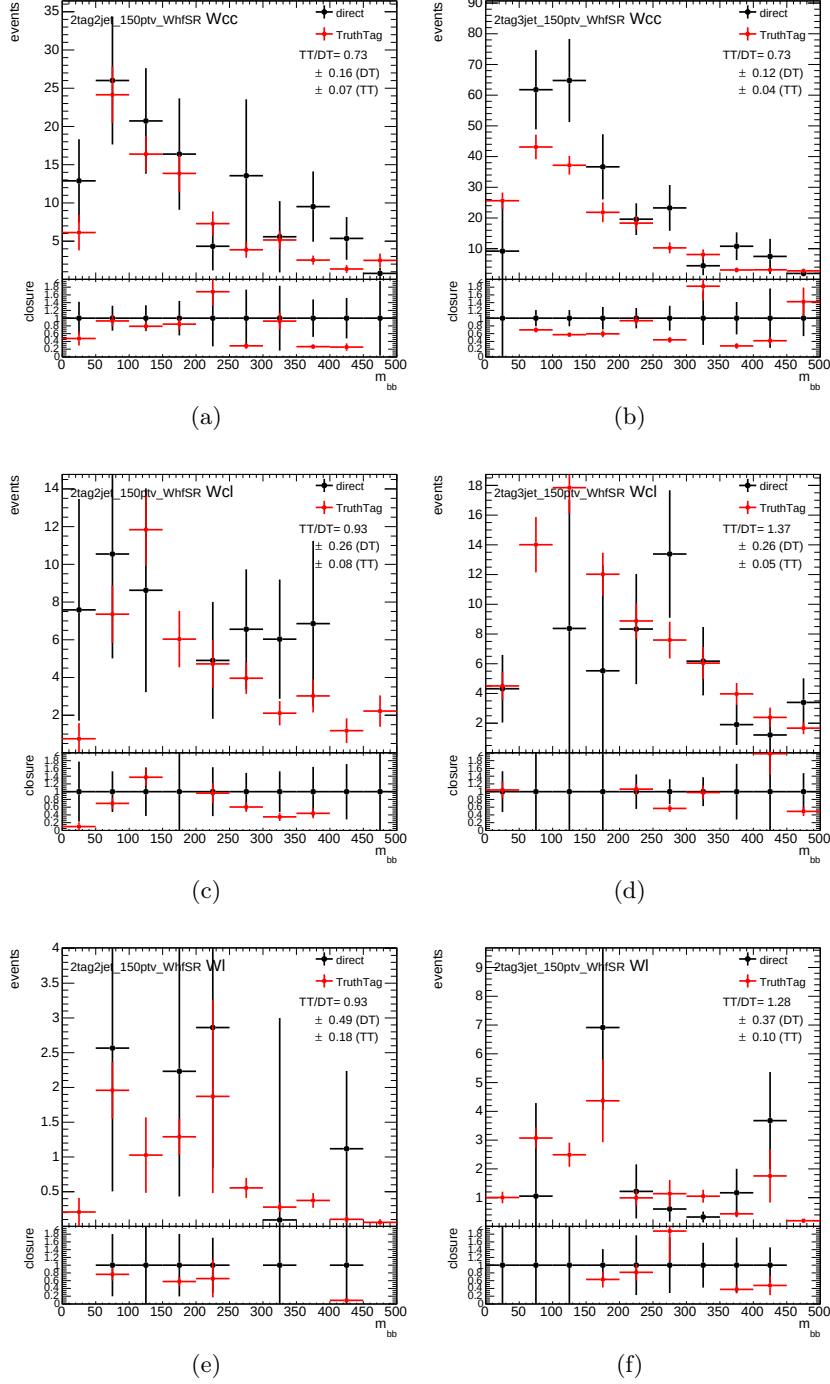


Figure 6.7 – Comparison of the m_{bb} distributions for $W + cc$ (top row), $W + cl$ (middle row) and $W + ll$ (bottom row), for the 2-jet (left column) and 3-jet (right column) signal regions with direct b -tagging (black) and parameterised tagging (red), in the 1-lepton $W + \text{HF}$ control region.

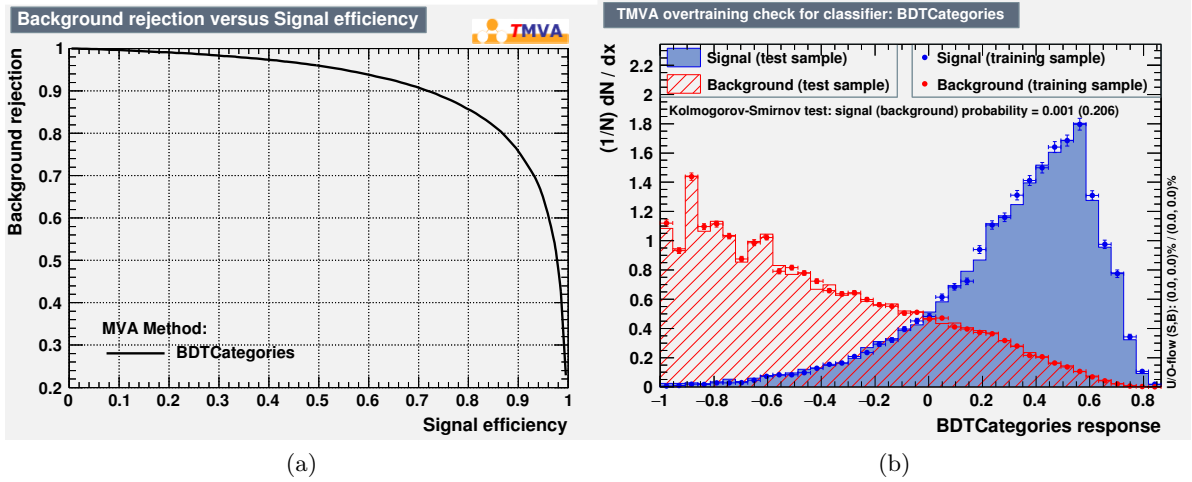


Figure 6.8 – (a) Expected background rejection as a function of the signal efficiency for the 0-lepton BDT. (b) The BDT distributions of signal (blue) and background (red) in the training (dots) and test (histograms) samples.

- $n_b(I[k, l])$ is the number of background events in the interval $I[k, l]$;
- z_s and z_b are parameters used to tune the algorithm.

The choice of the binning is performed in the following way:

1. Starting from the right-most bin (“last”) of the original histogram (*i.e.* from the region of large values of the BDT score, thus with less expected background events and better S/B , increase the range of the interval $I(k, \text{last})$ by adding one after the other, the bins from the right to the left, until two conditions are satisfied: $Z(I[k_0, \text{last}]) > 1$, and the MC statistical uncertainty in the bin is $< 20\%$.
2. Merge all the bins in the interval $I(k_0, \text{last})$ into a single bin and repeat the previous step, now starting from bin $k_0 - 1$.
3. Repeat steps 1 and 2 until k_0 is the left-most bin of the original histogram.

An optimisation procedure of the tuning parameters has led to the choice of $z_s = 10$, $z_b = 5$.

6.7 Multi-jet background estimation

Due to their large cross sections compared to the electroweak processes constituting the main backgrounds for the search presented here, multi-jet QCD events, in which jets are misidentified as leptons or misreconstructed and lead to a large, fake, E_T^{miss} , can give rise to a non-negligible background. Simulating a sufficiently high number of such events, and properly modelling the probability of jets faking leptons or E_T^{miss} , is very challenging. For this reason, data-driven techniques are used to estimate this background.

In the 0-lepton channel, a QCD-enriched sample is obtained by removing the $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ requirement applied in the nominal selection. A fit to the distribution of this variable is then performed to 3-jet events selected in data to determine the multi-jet yield. Multi-jet events tend to

peak at values close to zero, while electroweak backgrounds are typically characterised by larger values of this variable, as shown in Figure 6.9(b). In the fit, the multi-jet distribution is assumed to be described by an exponential function, $N \exp(-x/c)$; the electroweak background distributions are taken from the simulation, with floating normalisation factors for $t\bar{t}$ and for V +jets, and fixed normalisation for single-top and diboson production. The multi-jet yield and its shape parameter c are determined from the fit; once known, the expected multi-jet background in the signal region is easily computed. The resulting fit is shown in Figure 6.10. The multi-jet yield is found to be about 10% of the expected signal and less than 0.1% of the electroweak backgrounds. Moreover, the BDT distribution of events in data with low $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ is found to be similar to that of the electroweak backgrounds, and thus the small remaining multi-jet contribution can be “absorbed” in the floating normalisation factors of the electroweak backgrounds in the final fit. The same data-driven estimation technique cannot be used in the 0-lepton 2-jet region, because the stronger correlation between $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ and the other anti-QCD variables in 2-jet events implies that no multi-jet events with low $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ survive after having applied the other selection requirements, as shown in Figure 6.9 (a). However, it is observed – using a multi-jet MC sample generated with PYTHIA 8 with the A14 tune and the NNPDF2.3LO PDF set, and removing the b -tagging requirement to increase the number of events – that the $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ distribution of 2-jet and 3-jet events passing the other 0-lepton selection criteria should be similar. Figure 6.9(a) thus indicates that the electroweak backgrounds in 2-jet events are of the same order of magnitude as those in 3-jet events, while the multi-jet background is much smaller (since no events are seen near zero) and thus can be safely neglected in the analysis.

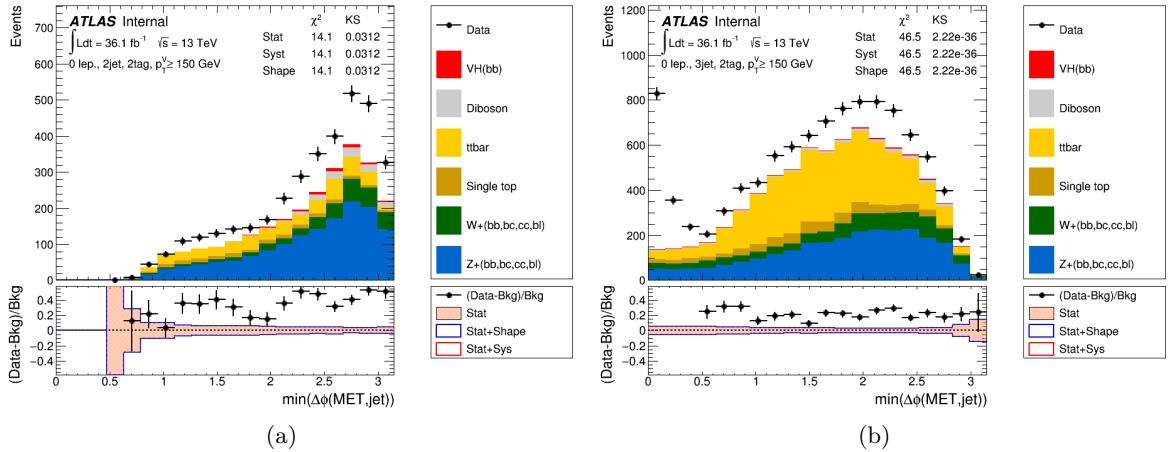


Figure 6.9 – Pre-fit $\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{jets})]$ distributions for the 0-lepton (a) 2-jet and (b) 3-jet categories excluding the selection on this variable.

In the 1-lepton channel, the multi-jet background arises mainly from leptons from semileptonic decays of heavy-flavour hadrons, with a small additional contribution from conversions of photons from π^0 decays. Such background is strongly suppressed by the lepton isolation criteria, but – due to its large cross section – some event still pass the selection. The multi-jet background yield is estimated with a fit to m_T^W . In this fit, the multi-jet distribution is taken as the distribution of events in a control region selected by inverting the lepton isolation requirement of the nominal selection and lowering the required number of b -tagged jets to one, after subtraction of the expected electroweak background distribution. In the fit to determine the multi-jet

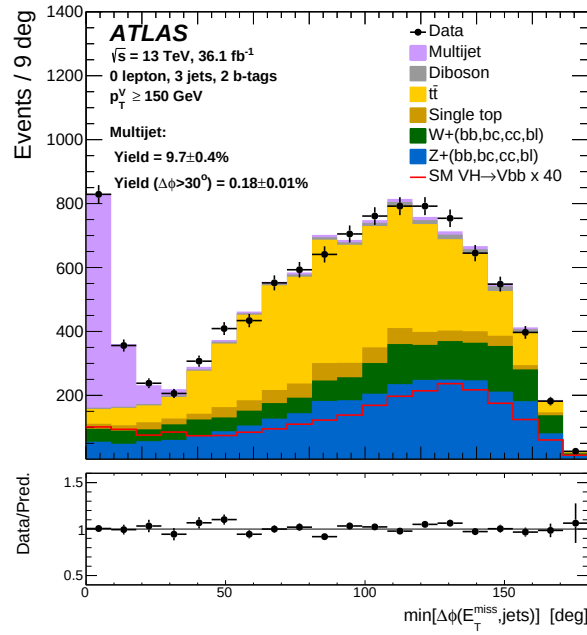


Figure 6.10 – Multi-jet estimate in the 0-lepton channel. The plot shows the fit to data of the $\min[\Delta\phi(E_T^{\text{miss}}, \text{jets})]$ distribution in the 0-lepton channel 3-jet category. The multi-jet contribution is parameterised as a falling exponential ($\exp(-cx)$), with parameter c determined in the fit itself, while the templates for the other backgrounds are fixed to the MC expectation. The normalisation of the $t\bar{t}$, W +jets and Z +jets are also determined in the fit, and are compatible with the values determined in the global likelihood fit used to extract the Higgs boson signal. The extracted multi-jet yield, together with the background normalisations, are also reported.

yield, the shapes of the m_T^W distribution of the electroweak backgrounds, $t\bar{t}$ and W +jets, are fixed from the simulation, while their normalisation is floating; to better constrain the W +jet normalisation, a simultaneous fit to the overall yield in the corresponding W +HF control region is performed. This procedure is applied separately in the electron and muon sub-channels, and in the 2-jet and 3-jet categories. The multi-jet contribution is found to be almost 5% of the total background contribution in the 2-jet category and about 0.5% in the 3-jet category; both numbers are affected by large relative uncertainties, between 60% and 200%. It is therefore a non-negligible background and is thus included explicitly in the final fit. The shape of the BDT discriminant for multi-jet events in the signal region is obtained in the same way as the m_T^W multi-jet template.

In the 2-lepton channel, the multi-jet background is estimated from a control sample of events with same-flavour, same-charge leptons. A three-component fit to the dilepton invariant mass distribution is performed. The components in the fit are the multi-jet background, the Z +jet background, and the other electroweak backgrounds. The multi-jet component is described by an exponential function with floating yield and parameter of the exponential. The shapes of the electroweak backgrounds are obtained from the simulation, as well as the normalisation of the electroweak backgrounds other than Z +jet (they are mostly due to top-quark background), while the normalisation of the Z +jet background is floating. The normalisation of the non Z +jet background needs to be fixed because its shape is quite similar to that of multi-jet events. It is seen from other control regions that the top background normalisation predicted by the simulation is in good agreement with the data and it does not need to be multiplied by scale factors largely different from one. The estimated contribution from multi-jet events to the 2-lepton signal region is 0.03% and 0.2% of the total background for the muon and electron sub-channels, respectively. It is about 8% of the expected signal but its BDT shape is similar to the one expected for the sum of the remaining backgrounds. For these reasons, as for the 0-lepton channel, the multi-jet component is not included in the final fit, and simply absorbed in the floating normalisation factors of the electroweak backgrounds in the final fit.

6.8 Systematic uncertainties

As described in Sec. 6.1, the results are derived from a fit to the distribution in data events of a discriminating variable, either BDT_{VH} or m_{bb} , in each analysis category. The data distribution is binned and is fitted with the sum of various “templates”, *i.e.* histograms representing the expected shapes of each signal or background process. Such templates are determined from the expected kinematic properties of such processes, predicted by the theoretical calculations implemented in the MC event generators and the cross section calculations used to normalise some of the simulated samples, and the expected experimental reconstruction, identification, and calibration performance (efficiencies, energy scale and resolution, ..). Systematic uncertainties on such templates arise those from *experimental uncertainties* in the performance of the ATLAS detector for the particles selected in the final states under study and in *theoretical uncertainties* – also denoted modelling uncertainties in the following – on the expected kinematic properties of the signal and background. There are also systematic uncertainties affecting the data-driven estimate of the multi-jet background template. In the following subsections the various sources of systematic uncertainties are described.

6.8.1 Experimental uncertainties

The main experimental uncertainties affecting the results are those in the b -tagging efficiency, followed by those in the jet energy scale and resolution. Smaller uncertainties arise from the lepton trigger, reconstruction and selection efficiency and calibration, from the E_T^{miss} reconstruction, and from the luminosity measurement. They are determined as follows:

- The b -tagging efficiency uncertainties are determined separately for b -jets, c -jets and light-flavour jets from control samples enriched in each one of these three types of jets. A detailed example of how such uncertainties are obtained for b -jets using a control sample selected with $t\bar{t}$ events has been given in the previous chapter. Simulation-to-data efficiency correction factors (scale factors), and corresponding uncertainties, are determined as a function of jet p_T (or p_T and η). The approximate size of these uncertainties are 2% for b -jets, 10% for c -jets and 30% for light jets. Additional uncertainties for $p_T > 300$ GeV are introduced due to the extrapolation to a p_T range where the size of the control samples is too small and MC-based estimates are used.
- The uncertainties in the jet energy scale and resolution are determined as a function of jet p_T and η from *in situ* measurements based on data control samples like balanced Z +jet, γ +jet or multi-jet events. An additional specific uncertainty from the simulation is introduced to account for differences in the calibration of b or c -jets with respect to light jets (which are largely dominant in the data control samples).
- The uncertainties in the reconstruction, identification, isolation and trigger efficiencies of leptons are determined from control samples of dileptons from decays of the Z boson, with a tag-and-probe technique. The uncertainties in the lepton energy calibration are determined from the invariant mass distributions of dileptons from the decays of Z , Υ and J/ψ bosons. The uncertainty in the peak position (width) of the reconstructed dilepton invariant mass distribution is translated into the uncertainty on the lepton energy scale (resolution). Such uncertainties have a very small impact on the result.
- The uncertainty on the E_T^{miss} reconstruction is due to the uncertainties in the jet and lepton energy scale and resolution (described in the previous two bullets), to the uncertainty on the momentum scale and resolution and the reconstruction efficiency of the tracks used to calculate the soft term, and to the contribution of the underlying event. In the 0-lepton channel, and in the 1-lepton muon channel, the uncertainties in the simulation-to-data E_T^{miss} trigger efficiency scale factors, determined from control samples of W +jets and $t\bar{t}$ events, are also considered.
- The uncertainty in the luminosity is 3.2%, as for the b -tagging efficiency calibration performed on the same amount of data. In addition, a pile-up uncertainty is computed as follows. In the nominal simulation the average number of interactions per bunch crossing is increased by 9% to improve the agreement between simulation and data. The full size of the correction is taken as an uncertainty.

6.8.2 Simulated background modelling uncertainties

Modelling uncertainties for the simulated backgrounds can affect either their overall normalisation, the relative acceptance of different analysis regions, or the shape of the distributions of the main kinematic variables that are used to build the discriminant used in the fit to the data.

Two methods are used to compute such uncertainties: comparisons between the samples produced with the nominal event generators and alternative samples produced with different event generators or with different settings of the same event generator, or comparisons between the nominal simulation and data in some dedicated control regions. The comparisons between nominal and alternative MC samples were usually performed at the particle-level, since it was possible to generate many more events than those that are passed through the full detector simulation, because event generation is much faster than detector simulation. In a few cases the events generated with alternative MC programs or settings were also simulated, so that the particle-level comparisons could be cross-checked at the detector level. Good agreement between the comparisons performed in the two approaches was found in such cases.

To compute acceptance uncertainties of a certain background process, all the corresponding MC samples (nominal and alternative) are normalised to the same production cross-section, and the differences between the acceptances predicted by the nominal and each of the alternative samples are summed in quadrature.

Shape uncertainties are determined separately for each event category. They are determined by comparing the shapes of the distributions of the variable under consideration in the nominal and alternative samples, after having normalised each sample to the same integral in each category. The largest shape difference between the alternative samples and the nominal sample is considered as the shape uncertainty. We only consider shape uncertainties for the distributions of the m_{bb} and p_T^V variables, which are the two BDT input variables with the highest signal-vs-background separation and are largely uncorrelated; it was observed that modifying these two distributions of the nominal sample by the corresponding shape uncertainties would be sufficient to obtain a BDT_{VH} distribution whose difference with that of the nominal MC sample is equal to or larger than that of each of the alternative MC samples.

The particle-level analysis is performed using the RIVET [116] framework, in which a selection as similar as possible to the detector-level one is implemented. The same p_T and η selections applied at detector-level to the reconstructed candidates are applied at particle-level to the stable particles of the truth record of the MC samples. Track (calorimeter) isolation variables are computed using the true charged (charged and neutral, excluding neutrinos) particles' transverse momenta. Jets are labelled as b , c or light based on a ΔR matching to b -hadrons or c -hadrons or neither, as described previously. The missing transverse energy is computed from the transverse momentum of the negative sum of the four-momenta of all the true stable particles, except neutrinos, in the detector acceptance, and the missing transverse momentum is computed similarly but using only the charged stable particles. At least two central jets are requested. Central jets are then ranked according to their flavour (with priority given to b -jets, than to c -jets and finally to light jets). The two highest-ranked are used to form the Higgs boson candidate, and are ordered according to their transverse momentum, in decreasing order. The true flavour of the two jets selected as the Higgs boson candidate decay products also determines the flavour-label of the event: bb , bc , bl , cc , cl or ll .

The 0-lepton particle-level selection is defined as follows:

- exactly zero leptons passing the p_T , η and isolation requirements corresponding to the VH -loose selection

- $E_T^{\text{miss}} > 150 \text{ GeV}$;
- $\Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < \pi/2$;
- $\min[\Delta\phi(E_T^{\text{miss}}, jets)] < 20^\circ$ (using the first 3 leading jets);
- $\sum p_T(jets) > 120(150) \text{ GeV}$ for 2(> 2)-jet events (the sum is over the first 2 leading central jets and the first additional jet in p_T);
- $p_T(j_1) > 45 \text{ GeV}$;
- $\Delta\phi(j_1, j_2) < 140^\circ$;
- $\Delta\phi((E_T^{\text{miss}}, j_1 + j_2) < 120^\circ$.

The 1-lepton particle-level selection is defined as follows:

- exactly one lepton passing the p_T , η and isolation requirements corresponding to the WH -signal selection and no extra lepton passing the p_T , η and isolation requirements corresponding VH -loose selection;
- $p_T^W > 150 \text{ GeV}$;
- $p_T(j_1) > 45 \text{ GeV}$.

The 2-lepton particle-level selection is defined as follows:

- exactly two same-flavour (and, in the case of muons, opposite-charge) leptons passing the p_T , η and isolation requirements corresponding to the VH -loose selection, of which at least one passing the ZH -signal selection;
- $71 \text{ GeV} < m_{\ell\ell} < 121 \text{ GeV}$;
- $p_T(j_1) > 45 \text{ GeV}$.

6.8.2.1 V +jets background uncertainties

The main contribution to the V +jets background originates from V +HF events. The V +HF background cross sections have large theoretical uncertainties; since such events are relatively abundant in the selected sample – and moreover for W +HF there is a dedicated control region

with good purity – the data are used to constrain their yield, thus avoiding such large uncertainties to propagate to the final results. Their overall normalisation, separately in the 2-jet and 3-jet categories, are thus determined directly from the fit to the data, and only acceptance and shape uncertainties are considered. V +light events ($V+cl$, $V+ll$) only constitute 1% or less of the background in each signal or control region, and only uncertainties on their normalisation are computed, as acceptance and shape uncertainties do not impact significantly the results.

Within the 2-jet or 3-jet categories, acceptance uncertainties affect the relative normalisations of V +HF events in the various signal and/or control regions: for Z +HF, this means an uncertainty in the ratio of number of events between the 0-lepton and the 2-lepton categories; for W +HF, this corresponds to an uncertainty in the ratio of event yields between the 0-lepton and 1-lepton categories, and – in the 1-lepton channel – in the ratio between the yield in the signal region and in the W +HF control region. Acceptance uncertainties are also considered for the relative contributions of $V+bb$, bc , bl , cc events to the V +HF yield; they are computed as uncertainties in the ratios of the $V+bc$, bl , cc yields over the $V+bb$ yield, separately for 0-lepton, 2-lepton 2-jet and 2-lepton 3-jet events for Z +HF, and for 0-lepton and 1-lepton events for W +HF.

The normalisation and acceptance uncertainties are determined by comparing the nominal SHERPA 2.2.1 sample to alternative samples produced with the same event generator but different settings of the renormalisation, factorisation, resummation and CKKW merging scales (varied independently between 0.5 and 2 times the nominal value). In addition, a contribution to these systematic uncertainties is also derived from the comparison between the nominal SHERPA sample and an alternative sample produced with MADGRAPH5_AMC@NLO v2.2.2 [85] with LO matrix elements calculated for real emission of up to four extra partons, using the NNPDF2.3LO PDF set, interfaced to PYTHIA 8 with the A14 tune for the modelling of the parton showering, the underlying event and pile-up. The final uncertainties are summarised in Tables 6.11–6.14.

Table 6.11 – Effect of modelling systematics on Z +jets normalisation and acceptance in the 0-lepton and 2-lepton regions. For systematic uncertainties implemented with a prior the effect of $1\text{-}\sigma$ variation is reported. The uncertainties labelled as Zbb act on the entire Z +HF background.

Process	Name	prior in region					
		2jet			$(\geq)3\text{jets}$		
		2l: medium p_T^V	2l: high p_T^V	0l	2l: medium p_T^V	2l: high p_T^V	0l
$Z+ll$	SysZclNorm	18%					
$Z+cl$	SysZlNorm	23%					
$Z+HF$	norm_Zbb	Floating Normalisation					
$Z+HF$	SysZbbNorm_L2_J3	–	–	–	30%	30%	–
$Z+HF$	SysZbbNorm_J3	–	–	–	–	–	17%
$Z+HF$	SysZbbNorm_0L	–	–	7%	–	–	7%

Shape uncertainties on the m_{bb} and p_T^V distributions of the V +HF background are estimated as follows. For Z +HF events, they are determined by comparing these distributions between data and Z +jets simulation, in control regions that are dominated by Z +jet production: they are the events passing the 2-lepton selection, on which an additional requirement $E_T^{\text{miss}}/\sqrt{s_T} < 3.5\sqrt{\text{GeV}}$ is applied to suppress the $t\bar{t}$ contamination, and the region $110 < m_{bb} < 140$ GeV is vetoed to remove VH signal events. To increase the size of the control sample, also events in which only one of the two signal jets is b -tagged are considered. The small contribution from non- Z +jet events is subtracted from the data using the simulation. Examples for the 2-tag control regions

Table 6.12 – The priors on the relative acceptance variations for Z +HF. The first column details the flavour components across which the acceptance variation is being considered, the second column lists the names of the corresponding nuisance parameter in the profile Likelihood Fit, the third contains the value of the prior and the fourth column the processes and categories to which this nuisance parameter is applied.

Category	Nuisance Parameter Name	Prior	Applied to
$Z+bc/Z+bb$	SysZbcZbbRatio	40%	$Z+bc$ events (0-lepton)
		40%	$Z+bc$ events (2-lepton 2jet)
		30%	$Z+bc$ events (2-lepton ≥ 3 jet)
$Z+bl/Z+bb$	SysZblZbbRatio	25%	$Z+bl$ events (0-lepton)
		28%	$Z+bl$ events (2-lepton 2jet)
		20%	$Z+bl$ events (2-lepton ≥ 3 jet)
$Z+cc/Z+bb$	SysZccZbbRatio	15%	$Z+cc$ events (0-lepton)
		16%	$Z+cc$ events (2-lepton 2jet)
		13%	$Z+cc$ events (2-lepton ≥ 3 jet)

Table 6.13 – Summary of the normalisation and acceptance uncertainties on the W +jets predictions in the various categories of the 0 and 1-lepton channels. For systematic uncertainties implemented with a prior the effect of $1\text{-}\sigma$ variation is reported. The uncertainties labelled as Wbb act on the entire W +HF background.

Process	Name	Prior in Region					
		0-lepton		1-lepton			
		2-Jets	3-Jets	WCR 2-Jets	SR 2-Jets	WCR 3-Jets	SR 3-Jets
$W+ll$	SysWclNorm	32%					
$W+cl$	SysWlNorm	37%					
$W+hf$	norm_Wbb	Floating Normalisation					
$W+HF$	SysWbbNorm_J3	–	18%	–	–	18%	18%
$W+HF$	SysWbbNorm_DWhfCR_L1	–	–	–	10%	–	10%
$W+HF$	SysWbbNorm_L0	5%	5%	–	–	–	–

Table 6.14 – The priors on the relative acceptance variations for W +HF. The first column details the flavour components across which the acceptance variation is being considered, the second column quotes the name of the corresponding nuisance parameter in the profile Likelihood Fit, the third contains the value of the prior and the fourth column the processes and categories to which this nuisance parameter is applied.

Category	Nuisance Parameter Name	Prior	Applied to
$W+bc/W+bb$	SysWbcWbbRatio	15%	$W+bc$ events (0-lepton)
		30%	$W+bc$ events (1-lepton)
$W+bl/W+bb$	SysWblWbbRatio	26%	$W+bl$ events (0-lepton)
		23%	$W+bl$ events (1-lepton)
$W+cc/W+bb$	SysWccWbbRatio	10%	$W+cc$ events (0-lepton)
		30%	$W+cc$ events (1-lepton)

are given in Figure 6.11. For W +HF events, there are no large control samples that can be used in a similar way as for Z +HF event, and shape uncertainties are determined from comparisons between the nominal and alternative MC samples used also to determine the W +HF acceptance uncertainties.

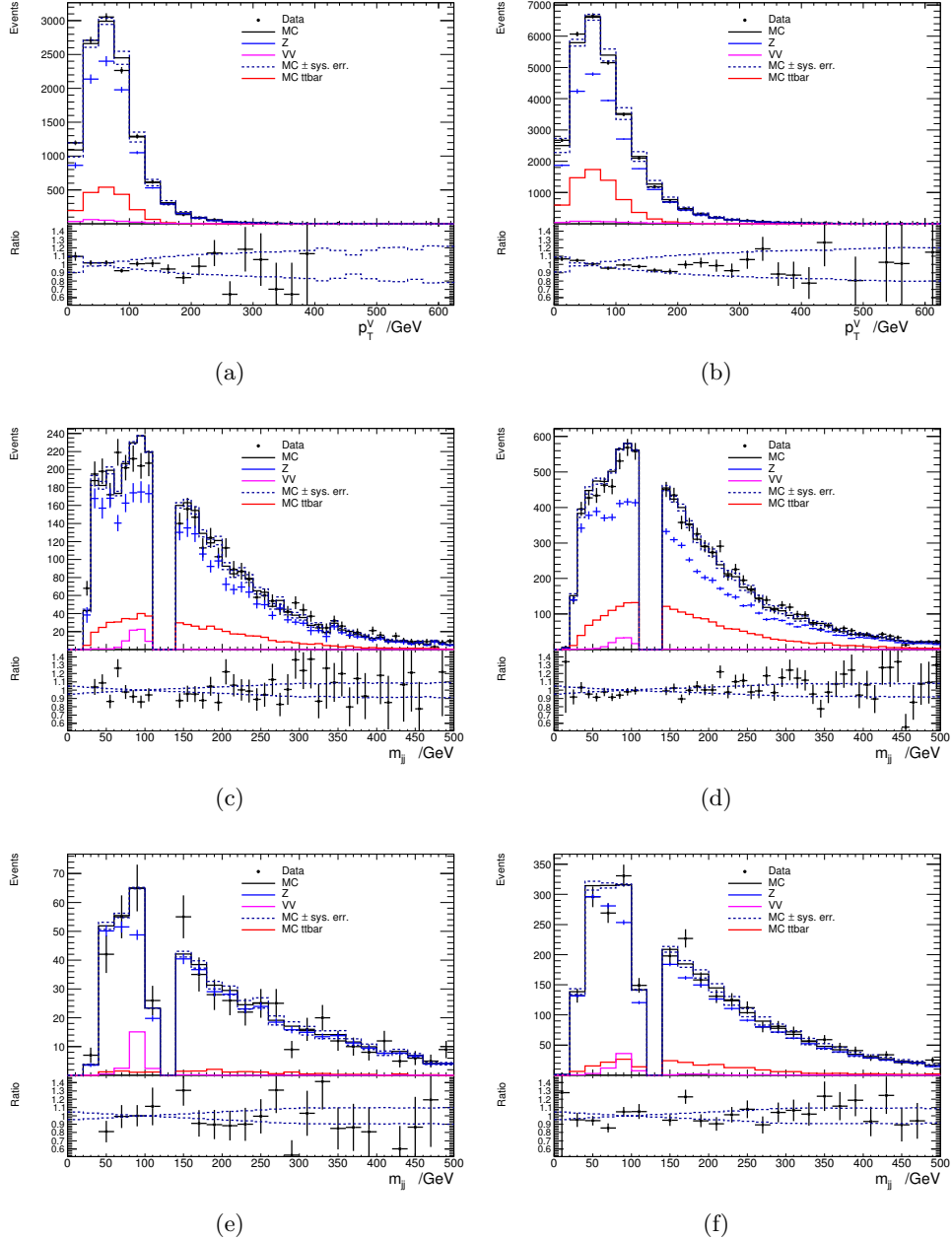


Figure 6.11 – The p_T^Z (a, b) and m_{jj} distribution for the medium p_T^Z region, $75 < p_T^Z < 150$ GeV (c, d) and high p_T^Z region, $p_T^Z > 150$ GeV (e, f) for the 2-tag 2-lepton control region of Z +jets events for 2 jets (a, c, e) and for ≥ 3 jets (b, d, f)

6.8.2.2 $t\bar{t}$ background uncertainties

$t\bar{t}$ production is another large source of background events. The overall normalisation is directly extracted from the fit, thanks to the top background control regions, separately for 0+1-lepton, 2-lepton 2-jet and 2-lepton 3-jet events. The particular treatment of the $t\bar{t}$ background normalisation factors, which are decorrelated between 0+1-lepton and 2-lepton channels, has two reasons. First, in the 2-lepton channel, the $t\bar{t}$ background is almost entirely due to dileptonic events ($t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu b\ell\nu\bar{b}$) with undetected neutrinos, while in the other two channels it is due to both dileptonic events with undetected leptons and semi-leptonic events ($t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}'\bar{b}$) with undetected quarks. Second, the $p_T(V)$ range accepted by the 0- and 1-lepton selections, $p_T(V) > 150$ GeV, is different from the one of the 2-lepton selection, $p_T(V) > 75$ GeV.

Acceptance uncertainties, as well as $m_{b\bar{b}}$ and p_T^V shape uncertainties, are then computed separately for $t\bar{t}$ events in the 0+1-lepton and 2-lepton channels. In the 0+1-lepton channels, uncertainties are determined in the yield ratios between 3-jet and 2-jet regions, between the 1-lepton W +HF control region and the signal region, and between the 1-lepton and the 0-lepton channels. In the 2-lepton channel there are no separated acceptance uncertainties, as the $e\mu$ control regions constrain the normalisations of each SR directly in the data. All these uncertainties are calculated from particle-level comparisons of the nominal sample (POWHEG interfaced to PYTHIA 8) to:

- a sample produced with a different matrix-element generator (MADGRAPH5_AMC@NLO interfaced to PYTHIA 8);
- a sample produced with a different parton-shower model (POWHEG interfaced to HERWIG 7 [90, 117] for the parton showering);
- a sample produced with the nominal generator but different settings that increase or decrease the amount of radiation.

The final normalisation and acceptance uncertainties are summarised in Tables 6.15–6.16.

Table 6.15 – Effect of modelling systematics on $t\bar{t}$ normalisation and acceptance in the 0 and 1-lepton analysis regions.

Systematic	0-lepton		1-lepton			
	2j	3j	WCR 2j	SR 2j	WCR 3j	SR 3j
norm_ttbar	floating normalisation					
SysttbarNorm_L0	8%	8%	–	–	–	–
SysttbarNorm_J2	9%	–	9%	9%	–	–
SysttbarNorm_DWhfCR_L1	–	–	25%	–	25%	–

6.8.2.3 Single-top background uncertainties

Single top-quark production is dominated by the t and Wt -channels. For the s -channel, which gives a tiny overall contribution, only a normalisation uncertainty is included. For the Wt and

Table 6.16 – Effect of modelling systematics on $t\bar{t}$ normalisation in the 2-lepton regions.

	2jet		≥ 3 jets	
	medium p_T^V [SR/CR]	high p_T^V [SR/CR]	medium p_T^V [SR/CR]	high p_T^V [SR/CR]
norm_ttbar_J2_L2	floating normalisation		–	
norm_ttbar_J3_L2	–		floating normalisation	

t channels normalisation, acceptance and shape uncertainties are evaluated. The normalisation uncertainties are estimated by summing in quadrature the variations in the theoretical cross sections obtained by changing the renormalisation and factorisation scales independently by 0.5 or 2.0 times the nominal value, or by changing the value of α_S or the PDFs according to the PDF4LHC prescription. Acceptance uncertainties are computed separately for the t and Wt channels, as the uncertainties in the fraction of events in the 2-jet and 3-jet signal regions. Shape m_{bb} and p_T^V uncertainties are also derived separately for the t and Wt channels. All these uncertainties are calculated from particle-level comparisons of the nominal sample (POWHEG interfaced to PYTHIA 6) to:

- a sample produced with a different parton-shower model (POWHEG interfaced to HERWIG++ for the parton showering);
- a sample produced with a different matrix-element generator and a different parton-shower model (MADGRAPH5_AMC@NLO interfaced to HERWIG++);
- a sample produced with the nominal generator but different settings that increase or decrease the amount of radiation.
- for Wt , a sample in which the overlap with the $t\bar{t}$ simulated sample from NLO diagrams is subtracted through the “diagram subtraction” (DS) technique instead of the “diagram removal” (DR) one used in the nominal samples [98, 111].

The final normalisation and acceptance uncertainties are summarised in Table 6.17.

6.8.2.4 Diboson background uncertainties

Diboson backgrounds are dominated by WZ and ZZ production. The WW process constitutes only less than 0.1% of the total background and thus only its overall normalisation uncertainty is considered. For WZ and ZZ instead, normalisation, acceptance and m_{bb} and p_T^V shape uncertainties are considered. Normalisation uncertainties (Table 6.18) are determined by comparing the overall yields predicted by the nominal SHERPA 2.2.1 sample with those from alternative SHERPA samples with factorisation, renormalisation and resummation scales halved or doubled independently, and from a sample generated with POWHEG interfaced to PYTHIA 8.

Acceptance uncertainties are computed for WZ events for the ratio of yields in the 0-lepton and 1-lepton channels, and for the ratio of yields in 2-jet vs 3-jet regions. For ZZ events, acceptance uncertainties are computed for the ratio of yields in the 0-lepton and 2-lepton channels, and for the ratio of yields in 2-jet vs 3-jet regions. For both WZ and ZZ , m_{bb} and p_T^V

Table 6.17 – Summary of all normalisation and acceptance uncertainties for the single top process with short descriptions and the name of the corresponding nuisance parameters.

Production	Uncertainty	Value	Source	Nuisance Parameter
s -channel	overall normalisation	4.6%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	stopsNorm
t -channel	overall normalisation	4.4%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	stoptNorm
t -channel	2 jet region acceptance	17%	sum in quadrature of deviations in alternative generators	correlated with 2 jet and 3 jet case stoptAcc
t -channel	3 jet region acceptance	20%	sum in quadrature of deviations in alternative generators	correlated with overall and 3 jet case stoptAcc
Wt channel	overall normalisation	6.2%	sum in quadrature of μ_R , μ_F , α_S and PDF uncertainties	stopWtNorm
Wt channel	2 jet region normalisation	35%	sum in quadrature of deviations in alternative generators	correlated with 2 jet and 3 jet case stopWtAcc
Wt channel	3 jet region normalisation	41%	sum in quadrature of deviations in alternative generators	correlated with overall and 3 jet case stopWtAcc
				correlated with overall and 2 jet case

Table 6.18 – Summary of all systematic uncertainties on the diboson cross section including their value, source and the corresponding nuisance parameter name.

Sys Name	source	Norm. effect	applied to
SysWWNorm	overall cross section uncertainty	25%	WW in all regions
SysWZNorm	overall cross section uncertainty	26%	WZ in all regions
SysZZNorm	overall cross section uncertainty	20%	ZZ in all regions

shape uncertainties are estimated. All these uncertainties are determined from the same scale variations and alternative samples described before (Table 6.19). Scale variation uncertainties for the acceptance in the jet multiplicity categories are derived using the Stewart–Tackmann method [118]. Additional uncertainties from the parton-shower and underlying-event modeling are derived from a comparison of events generated with POWHEG interfaced to either PYTHIA 8 or HERWIG++ (Table 6.20). PDF and α_s uncertainties are found to have a negligible impact on the acceptance and on the $m_{b\bar{b}}$ and p_T^V shapes, compared to the other sources of uncertainty.

Table 6.19 – Summary of the systematic uncertainties on the VZ acceptance in each analysis region and on the p_T^V and $m_{b\bar{b}}$ shapes originating from altering the QCD scale, including their nuisance parameter name.

NP name	0l: $ZZ \rightarrow \nu\nu b\bar{b}$		1l: $WZ \rightarrow \ell\nu b\bar{b}$		2l: $ZZ \rightarrow \ell\ell b\bar{b}$	
	2j	3j	2j	3j	2j	$\geq 3j$
SysVZ_QCDscale_J2	10.3%	–	12.7%	–	11.9%	–
SysVZ_QCDscale_J3	-15.2%	+17.4%	-17.7%	+21.2%	-16.4%	+10.1%
SysVZ_QCDscale_JVeto	–	+18.2%	–	+19.0%	–	–
SysVZ_QCDscale_VPT	shape					
SysVZ_QCDscale_MBB	shape					

Table 6.20 – Summary of the effects of parton shower and underlying event variations on the VZ acceptance in each analysis region and on the p_T^V and $m_{b\bar{b}}$ shapes, including their nuisance parameter name.

NP name	0l: $ZZ \rightarrow \nu\nu b\bar{b}$		1l: $WZ \rightarrow \ell\nu b\bar{b}$		2l: $ZZ \rightarrow \ell\ell b\bar{b}$	
	2j	3j	2j	3j	2j	$\geq 3j$
SysVZ_UEPS_Acc	5.6%	5.6%	3.9%	3.9%	5.8%	5.8%
SysVZ_UEPS_32JR	–	7.3%	–	10.8%	–	3.1%
SysVZ_UEPS_VPT	shape					
SysVZ_UEPS_MBB	shape					

6.8.3 Multi-jet background uncertainties

In the 0-lepton and 2-lepton channels the multi-jet background is negligible and the distribution of the discriminant used in the fit is similar between multi-jet events and the sum of the other backgrounds, such that the multi-jet background can be “absorbed” in the floating normalisation of the other backgrounds in the fit. In the 1-lepton channel, the multi-jet yield and BDT_{VH} distribution are determined from a data control sample, and are affected by uncertainties that are considered uncorrelated between the electron and muon sub-channels. Such uncertainties are estimated from the variations in the yields and BDT shapes obtained by changing the definition of the multi-jet control region, or the normalisation of the top and V +jets backgrounds in the control region, or fitting the E_T^{miss} distribution instead of the m_T^W one to extract the multi-jet yield.

6.8.4 Signal modelling uncertainties

The signal overall normalisation is determined from the fit to the data in the nominal and dijet-mass analyses; in the diboson analysis, it is set to the SM prediction compiled by the LHC Higgs cross section working group, with the following theoretical uncertainties.

- The production cross section is affected by the uncertainties in the proton PDFs and in the value of α_s , as well as from the missing higher-order terms in the fixed-order calculations. The effect of the PDF uncertainties is estimated by recalculating the production cross section with the 100 alternative replicas of the PDF4LHC15_NNLO_MC PDF set and taking the 68% confidence-level (CL) interval of the computed cross sections. The effect of the α_s uncertainty is determined by varying α_s by plus or minus one times its uncertainty in the calculation. The impact of the missing QCD higher orders in the calculation is estimated by varying the factorisation and renormalisation scales independently between 1/3 and 3 times the nominal value.
- The predicted $H \rightarrow b\bar{b}$ branching ratio is affected by uncertainties due to missing higher-order QCD and electroweak corrections, and to the uncertainties in the b -quark mass and in the value of α_s . The total uncertainty on the branching ratio is 1.7% [119].

The inclusive production cross sections for the various signal processes are summarised in Table 6.21. The uncertainties in the VH cross section and in the $H \rightarrow b\bar{b}$ branching ratio are summarised in Table 6.22.

Table 6.21 – Inclusive cross section for the signal processes.

Process	order	cross section (pb)
WH	NNLO(QCD)+NLO(EW)	1.37 ± 0.04
W^+H	NNLO(QCD)+NLO(EW)	0.84
W^-H	NNLO(QCD)+NLO(EW)	0.53
ZH	NNLO(QCD)+NLO(EW)	$0.88^{+0.04}_{-0.03}$
$gg \rightarrow ZH$	NLO+NLL(QCD)	0.12
$qq \rightarrow ZH$	difference	0.76

Table 6.22 – Summary of all systematic uncertainties on the VH cross section including their value, source and the corresponding nuisance parameter name.

Sys Name	source	Norm. effect	applied to
ATLAS_BR_bb	$H \rightarrow b\bar{b}$ decay uncertainties (HO effects, m_b , α_s)	1.7%	all VH processes
ATLAS_QCDscale_VH	QCD scale uncertainty	0.7%	$qq \rightarrow VH$ processes
ATLAS_QCDscale_ggZH	QCD scale uncertainty	27%	$gg \rightarrow ZH$
ATLAS_pdf_Higgs_VH	PDF+ α_s uncertainty	1.9%	$qq \rightarrow WH$
		1.6%	$qq \rightarrow ZH$
ATLAS_pdf_Higgs_ggZH	PDF+ α_s uncertainty	5.0%	$gg \rightarrow ZH$

Acceptance and shape uncertainties arise from several sources and are computed in the following way:

- uncertainties due to the missing higher-order QCD corrections are computed from the nominal POWHEG+MINLO+PYTHIA 8 sample in which the generator weights corresponding to alternative values (half or twice of the nominal value) of the factorisation and renormalisation scales (Table 6.23). The Stewart-Tackmann method is used to compute the acceptance uncertainties for the N_{jet} categories. This leads to various uncertainties due to the acceptance of the $N_{\text{jet}} \geq 2$ and $N_{\text{jet}} \geq 3$ requirements and – for the 0 and 1-lepton channel – the $N_{\text{jet}} \geq 4$ veto. Shape uncertainties for m_{bb} and p_T^V are derived by parametrising with a first-order polynomial for p_T^V and a second-order polynomial for m_{bb} the ratio between the varied and nominal distribution and taking the envelope among all the variations. For both variables, the shape uncertainties are determined separately for the 2-jet and 3-jet categories.
- uncertainties due to the parton shower and underlying event model are computed from the difference between the nominal POWHEG+MINLO+PYTHIA 8 sample and the alternative POWHEG+MINLO+HERWIG 7 sample, which uses the Herwig 7 parton shower and the H7-UE-MMHT tune. Additional uncertainties are computed from the difference between a MADGRAPH5_AMC@NLO sample interfaced to PYTHIA 8 with the A14 tune, and alternative samples produced with the same generator but with different settings of the A14 tune. The envelope of the two uncertainties is considered as the total uncertainty,

computed separately for the total acceptance, for the relative acceptance between 3-jet and 2-jet categories, and for the shapes of the m_{bb} and p_T^V distributions (Table 6.24).

- uncertainties due to the PDFs and the value of α_s are computed from the difference between the nominal POWHEG+MiNLO+PYTHIA 8 sample, whose generator weights correspond to the nominal PDFs and the nominal value of α_s of the PDF4LHC15_NLO_30_PDFAS set, to the 32 alternative PDF replicas of the PDF4LHC15_NLO_30_PDFAS set, corresponding to 30 PDF variations and 2 α_s variations (Table 6.25). The acceptance uncertainties are found to be similar for 2-jet and 3-jet categories.

Table 6.23 – Summary of the systematic uncertainties on the VH acceptance in each analysis region and on the p_T^V and m_{bb} shapes originating from altering the QCD scale, including their nuisance parameter name. The minus signs in the cells mean the uncertainties are negligible for the jet multiplicity due to the splitting.

NP name	0l: $ZH \rightarrow \nu\nu bb$		1l: $WH \rightarrow \ell\nu bb$		2l: $ZH \rightarrow \ell\ell bb$	
	2j	3j	2j	3j	2j	$\geq 3j$
QCDscale_VH_ANA_hbb_J2	6.9%	–	8.8%	–	3.3%	–
QCDscale_VH_ANA_hbb_J3	-7%	+5%	-8.6%	+6.8%	-3.2%	+3.9%
QCDscale_VH_ANA_hbb_JVeto	–	-2.5%	–	3.8%	–	–
QCDscale_VH_ANA_hbb_VPT	shape					
QCDscale_VH_ANA_hbb_MBB	shape					

Table 6.24 – Summary of the effects of parton shower and underlying event variations on the VH acceptance in each analysis region and on the p_T^V and m_{bb} shapes, including their nuisance parameter name.

NP name	0l: $ZH \rightarrow \nu\nu bb$		1l: $WH \rightarrow \ell\nu bb$		2l: $ZH \rightarrow \ell\ell bb$	
	2j	3j	2j	3j	2j	$\geq 3j$
ATLAS_UEPS_VH_hbb	10.0%	10.0%	12.1%	12.1%	13.9%	13.9%
ATLAS_UEPS_VH_hbb_32JR	–	13.0%	–	12.9%	–	13.4%
ATLAS_UEPS_VH_hbb_VPT	shape					
ATLAS_UEPS_VH_hbb_MBB	shape					

Table 6.25 – Summary of all systematic uncertainties on the VH acceptance and shapes originating from altering the PDF and α_s uncertainties, including their corresponding nuisance parameter name.

NP name	0l: $ZH \rightarrow \nu\nu bb$		1l: $WH \rightarrow \ell\nu bb$		2l: $ZH \rightarrow \ell\ell bb$	
	2j	3j	2j	3j	2j	$\geq 3j$
pdf_HIGGS_VH_ANA_hbb	1.1%	1.1%	1.3%	1.3%	0.5%	0.5%
pdf_VH_ANA_hbb_VPT	shape					
pdf_VH_ANA_hbb_MBB	shape					

6.9 Statistical Analysis

The signal yield in the selected data is determined by a maximum likelihood fit to the BDT distribution. The fit is based on the RooStats framework [120, 121]. The parameter of interest (POI) of the fit is the signal strength μ , defined as the ratio between the observed signal yield and the expected SM Higgs boson yield. The signal strength is assumed to be the same in each category, corresponding to the hypothesis that the VH cross section times $H \rightarrow b\bar{b}$ branching ratio in data is a factor μ times the SM prediction, independently of the vector boson type (W or Z) and of the ZH production process (quark- or gluon-induced).

The likelihood function is built as the product, over all the bins of the BDT distribution, of Poisson probability terms for the observed event yield in data, compared to the sum of the expected signal and background yields:

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \left[\prod_{i \in \text{bins}} \text{Pois} \left(n^i | \mu \nu_s^i(\boldsymbol{\theta}) + \nu_b^i(\boldsymbol{\theta}) \right) \right], \quad (6.4)$$

where n^i is the number of events in data and $\mu \nu_s^i$ and ν_b^i are the expected signal and background yields in each histogram bin i .

Floating background normalisations, and systematic uncertainties, enter the likelihood function through a set of “nuisance parameters” (NP) $\boldsymbol{\theta}$, which the expected numbers of signal and background events depend on. For each nuisance parameter corresponding to a systematic uncertainty, the likelihood function is multiplied by a “penalty term” that constrains the value of the systematic uncertainty around its estimate obtained from external sources (data control samples, theoretical calculations), within the uncertainty on such estimate. The penalty terms are Gaussian functions of the nuisance parameter θ with mean equal to zero and width equal to one, and the yields are multiplied by a term of the form:

$$e^{\sqrt{\log(1+\sigma^2)}\theta}, \quad (6.5)$$

where σ is the “best estimate” of the relative uncertainty, such that the the rates in each category are log-normally distributed, preventing normalisation factors from becoming negative in the fit.

The uncertainties in the background predictions due to the limited number of simulated events are also accounted for in the likelihood function by including an additional nuisance parameter per bin, using the Beeston–Barlow “light” technique [122]. For each bin i of the discriminant used in the final fit, the Poisson term of the likelihood function

$$\text{Pois} \left(n^i | \mu \nu_s^i(\boldsymbol{\theta}) + \nu_b^i(\boldsymbol{\theta}) \right) \quad (6.6)$$

is modified by introducing a nuisance parameter γ_i (with nominal value equal to one) that multiplies ν_b^i , and a multiplicative Poisson constraint for the true number of background events given the number of events predicted by the simulation:

$$\text{Pois} \left(n^i | \mu \nu_s^i(\boldsymbol{\theta}) + \gamma_i \nu_b^i(\boldsymbol{\theta}) \right) \text{Pois}(m_i | \gamma_i \tau_i), \quad (6.7)$$

where

$$m_i = \left(\frac{\nu_b^i}{\delta_i} \right)^2, \quad (6.8)$$

$$\tau_i = \left(\frac{\nu_b^i}{\delta_i} \right)^2, \quad (6.9)$$

and δ_i is the MC statistical uncertainty on ν_b^i . The Poisson constrain expressed in terms of $\left(\frac{\nu_b^i}{\delta_i} \right)^2$ corresponds to the fact that the equivalent size of a MC sample with relative uncertainty δ_i/ν_b^i is indeed $\left(\frac{\nu_b^i}{\delta_i} \right)^2$; if we generated a new Monte Carlo sample, m_b would fluctuate about τ_b . The γ_i NP only multiplies the background expectation since the signal expectation is affected by much smaller MC statistical uncertainties. In the standard version of the Barlow-Beeston technique, for each background contribution a γ NP is introduced; in this “light” version, which has been found in the literature to work reasonably well and permits a significant reduction of the fit complexity, only a nuisance parameter per bin – corresponding to the total background – is introduced.

The profile likelihood ratio test statistic, q_μ , is defined as follows:

$$q_\mu = -2 \ln \Lambda_\mu, \quad (6.10)$$

where

$$\Lambda_\mu = \mathcal{L}(\mu, \hat{\theta}_\mu) / \mathcal{L}(\hat{\mu}, \hat{\theta}), \quad (6.11)$$

Here $\hat{\mu}$ and $\hat{\theta}$ are the parameters that maximise the likelihood (“unconditional fit”), and $\hat{\theta}_\mu$ are the nuisance parameter values that maximise the likelihood for a given value of μ (“conditional fit”).

The compatibility of the data with the background-only hypothesis, used to identify the presence of a significant excess if the probability p_0 (called the “ p -value of the background-only hypothesis”) of such compatibility is sufficiently small, is evaluated with the test statistic $q_0 = -2 \ln \Lambda_0$. The measured signal strength is $\hat{\mu} \pm \sigma_\mu$, where σ_μ is determined from the variation of q_μ by one unit. The expected p_0 and signal strength are determined by applying the same statistical procedures to a so-called “Asimov” dataset, obtained by replacing the data in each input bin with the expected yields from the simulation with the nominal values of the nuisance parameters (“pre-fit” expected results), or with all the nuisance parameters fixed to the values ($\hat{\theta}$) from the fit to the data, except for the signal strength parameter, which is set equal to one (“post-fit”, conditional $\mu = 1$ expected results).

6.9.1 Fit inputs

The signal and control regions used in the fit have been summarised in Table 6.8. The primary inputs to the fit are the distributions of BDT_{VH} in the 8 signal regions. Additional inputs are the event yields in the two 1-lepton W +HF control regions and the m_{bb} distributions or the event yields in the four 2-lepton ($e\mu$) top-quark control regions.

The following components are included in the fit:

- signal VH , $H \rightarrow b\bar{b}$ (summed over all production modes);

- Z +jets and W +jets. The V +jets backgrounds are split into three components, V +HF, $V+cl$, and $V+ll$, depending on the origin of the two jets used to reconstruct the Higgs boson;
- $t\bar{t}$;
- single-top (summed over the s -, t -, and Wt -channels);
- diboson (sum of WW , WZ , ZZ);
- multi-jet background (for the 1-lepton channel only).

The choice of the components to fit, as well as of which nuisance parameters to be allowed to float freely in the fit, or on how to correlate or decorrelate various nuisance parameters among different categories, has been the result of various studies of the fit stability, closure, sensitivity to the signal, and fitted correlations between the various parameters.

For the multi-jet background, as explained before, the prediction is obtained from data control samples. For the other backgrounds, the predictions are from the simulation and the theoretical cross sections, with some exception indicated below. Parameterised b -tagging is used to obtain the WW , $V+cl$, $V+cc$, and $V+ll$ samples predictions, while direct b -tagging is used in the other cases.

6.9.2 Nuisance parameters: normalisation and systematic uncertainties

All parameters of the likelihood function other than the parameter of interest(s) that are floating in the fit are nuisance parameters. They can be classified into two categories: unconstrained normalisation factors, which float freely in the fit, and correspond to global rescaling factors of some background components, and parameters associated to systematic uncertainties that have external constraints, implemented as multiplicative penalty terms in the likelihood function.

The fit model contains eight freely-floating normalisation parameters, one is the parameter of interest μ , *i.e.* the VH , $H \rightarrow b\bar{b}$ signal strength; the other seven are

norm_Zbb_J2, norm_Zbb_J3: normalisation of Z +HF background (decorrelated between the 2-jet and 3 (or more) jet categories);

norm_Wbb_J2, norm_Wbb_J3: normalisation of W +HF background (decorrelated between the 2-jet and 3 (or more) jet categories);

norm_ttbar, norm_ttbar_J2_L2, norm_ttbar_J3_L2: $t\bar{t}$ background normalisation (decorrelated between 0+1 lepton, and 2-lepton 2-jet and 2-lepton 3-jet categories).

Several additional nuisance parameters constrain the relative or absolute normalisation of the backgrounds (knowing their cross section and acceptance), as well as their shapes. Priors on these nuisance parameters are obtained from data-MC comparison or MC studies, as described in Sections 6.8.2 and 6.8.3, and are summarised in Tables 6.26, 6.27, 6.28. Experimental systematic uncertainties briefly summarised in Section 6.8.1 are also included in the fit through additional nuisance parameters.

Table 6.26 – Summary of the systematic uncertainties in the background modelling for $Z + \text{jets}$, $W + \text{jets}$, $t\bar{t}$, single top quark and multi-jet production. An “S” symbol is used when only a shape uncertainty is assessed. The regions for which the normalisations float independently are listed in brackets.

$Z + \text{jets}$	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + bb$ normalisation	Floating (2-jet, 3-jet)
$Z + bc\text{-to-}Z + bb$ ratio	30 – 40%
$Z + cc\text{-to-}Z + bb$ ratio	13 – 15%
$Z + bl\text{-to-}Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
$W + \text{jets}$	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
$W + bb$ normalisation	Floating (2-jet, 3-jet)
$W + bl\text{-to-}W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc\text{-to-}W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc\text{-to-}W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
$W + \text{HF CR to SR ratio}$	10% (1-lepton)
m_{bb}, p_T^V	S
$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
$W + \text{HF CR to SR ratio}$	25%
m_{bb}, p_T^V	S
Single top quark	
Cross-section	4.6% (s -channel), 4.4% (t -channel), 6.2% (Wt)
Acceptance 2-jet	17% (t -channel), 35% (Wt)
Acceptance 3-jet	20% (t -channel), 41% (Wt)
m_{bb}, p_T^V	S (t -channel, Wt)
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 100 – 400% (3-jet)
BDT template	S

Table 6.27 – Summary of the systematic uncertainties in the background modelling for diboson production. “PS/UE” indicates parton shower / underlying event. An “S” symbol is used when only a shape uncertainty is assessed. When determining the $(W/Z)Z$ diboson production signal strength, the normalisation uncertainties in ZZ and WZ production are removed.

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations (var.)	10 – 18% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	5.6% (0-lepton), 5.8% (2-lepton)
Acceptance from PS/UE var. for 3 jets	7.3% (0-lepton), 3.1% (2-lepton)
m_{bb}, p_T^V , from scale var.	S (correlated with WZ uncertainties)
m_{bb}, p_T^V , from PS/UE var.	S (correlated with WZ uncertainties)
m_{bb} , from matrix-element var.	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale var.	13 – 21% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	3.9%
Acceptance from PS/UE var. for 3 jets	11%
m_{bb}, p_T^V , from scale var.	S (correlated with ZZ uncertainties)
m_{bb}, p_T^V , from PS/UE var.	S (correlated with ZZ uncertainties)
m_{bb} , from matrix-element var.	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%

Table 6.28 – Summary of the systematic uncertainties in the signal modelling. “PS/UE” indicates parton shower / underlying event. An “S” symbol is used when only a shape uncertainty is assessed.

Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \rightarrow WH$), 1.6% ($qq \rightarrow ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5 – 8.8% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	10 – 14% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	13%
Acceptance from PDF+ α_S var.	0.5 – 1.3%
m_{bb}, p_T^V , from scale var.	S
m_{bb}, p_T^V , from PS/UE var.	S
m_{bb}, p_T^V , from PDF+ α_S var.	S

6.9.3 Nuisance parameters: smoothing and pruning

When a systematic uncertainty - such as the JES uncertainties – may introduce changes in the events selected, additional statistical fluctuations may be introduced in the corresponding BDT_{VH} or m_{bb} template. In that case, the varied templates of each analysis region are smoothed, by merging bins together until the statistical uncertainty in each bin becomes smaller than 5%, with the constraints that the BDT_{VH} templates are monotonous, and the m_{bb} templates have at most a local maximum.

To reduce the complexity of the fit, systematic uncertainties that have a negligible impact on the final results are pruned away, region by region. The following pruning strategies are adopted. A normalisation (shape) uncertainty is dropped if it induces a template variation below 0.5% (below 0.5% in all bins). In regions where the signal contribution is less than 2% of the total background, nuisance parameters leading to a variation of the total background prediction by less than 0.5% are pruned. Shape uncertainties for which the $+1\sigma$ and -1σ variations are expected to lead to variations in opposite directions (referred to as "up" and "down"). The systematic variations for which the difference between 'up' and 'down' is smaller than the difference between "up" or "down" and the nominal shape are also pruned.

Studies were performed to verify that the smoothing and pruning procedures do not induce any bias in the result.

6.10 Results

The fit described in the previous section is performed simultaneously to the signal and control regions selected in the 36 fb^{-1} of 13 TeV pp collisions collected in 2015 and 2016. The fitted values of the background scale factors that are freely floating in the fit are summarized in Table 6.29. They agree with the SM predictions within their uncertainties; for V +HF, such uncertainties are rather large, and the nominal scale factors are around 1.2–1.3.

The fitted signal and background yields in the eight signal regions are given in Table 6.30. The sum of the signal and background yields in each signal region is in good agreement with the data. The fitted signal yield corresponds to a signal strength of

$$\mu = 1.20_{-0.23}^{+0.24}(\text{stat.})_{-0.28}^{+0.34}(\text{syst.}), \quad (6.12)$$

Table 6.29 – Factors applied to the nominal normalisations of the $t\bar{t}$, W +HF, and Z +HF backgrounds, as obtained from the global fit to the 13 TeV data for the nominal multivariate analysis, used to extract the Higgs boson signal. The errors include the statistical and systematic uncertainties.

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
W +HF 2-jet	1.22 ± 0.14
W +HF 3-jet	1.27 ± 0.14
Z +HF 2-jet	1.30 ± 0.10
Z +HF 3-jet	1.22 ± 0.09

in good agreement with the Standard Model prediction.

Table 6.30 – The fitted Higgs boson signal and background yields for each signal region category in each channel after the full selection of the multivariate analysis. The yields are normalised by the results of the global likelihood fit. All systematic uncertainties are included in the indicated uncertainties. An entry of “–” indicates that a specific background component is negligible in a certain region, or that no simulated events are left after the analysis selection.

Signal regions	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2- b -tag		$p_T^V > 150$ GeV, 2- b -tag		75 GeV $< p_T^V < 150$ GeV, 2- b -tag		$p_T^V > 150$ GeV, 2- b -tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	≥ 3 -jet	2-jet	≥ 3 -jet
$Z + ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	–	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z + cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
$Z + \text{HF}$	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W + ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W + cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
$W + \text{HF}$	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	–	–	102 ± 66	27 ± 68	–	–	–	–
Multi-jet μ sub-ch.	–	–	133 ± 99	90 ± 130	–	–	–	–
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708

For a Higgs boson mass of 125 GeV the p_0 of the data is 0.019%, corresponding to a significance of 3.5 standard deviations, providing an evidence of the $H \rightarrow b\bar{b}$ decay and of VH production. The expected p_0 , when the backgrounds are normalised to the values obtained from the fit to the data, is 0.12%, corresponding to an expected significance of 3.0σ . The contribution to the observed and expected significance from each channel is shown in Table 6.31.

Table 6.31 – The expected and observed p_0 and significance values (in standard deviations) for the individual lepton channels and their combination using 36 fb^{-1} of 13 TeV pp collisions. The expected values are evaluated assuming a SM Higgs boson with a mass of 125 GeV.

Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5

The post-fit BDT_{VH} distributions of the eight signal regions are shown in Figures 6.12 and 6.13.

The post-fit yields or m_{bb} distributions of the two W +HF control regions and the four top background control regions used in the fit are shown in Figures 6.14.

For illustration purposes, figure 6.15 shows the data, background and signal yields of the eight signal regions grouped together as a function of $\log(S/B)$, where S and B are the fitted signal and background yields, respectively.

The uncertainty on the signal strength is dominated by systematic uncertainties (in which, however, some uncertainties that are of statistical origin – like the freely floating background normalisations – have been also included). The contribution of each group of sources of systematic uncertainties to the total uncertainty is summarised in Table 6.32. The contribution of each group is determined by fixing all the corresponding NPs to their fitted values, repeating the fit, and computing the difference in quadrature between the uncertainties for $\hat{\mu}$ in the nominal fit and in this alternative fit and in the nominal fit.

The signal modelling uncertainties are the largest ones, followed by the uncertainty due to the limited size of the simulated samples, the uncertainty in the modelling of the backgrounds, and the uncertainty in the b -jet tagging efficiency.

In Figures 6.16 to 6.18 the nuisance parameter pulls and constraints are shown for the unconditional combined fit, performed on an Asimov dataset and on 2015+2016 data.

The correlation matrices corresponding to the combined fit when fitting an Asimov dataset and data can be found in Figure 6.19. Only correlations among parameters with a magnitude greater than 0.25 are shown.

The fit is repeated by allowing either the three lepton channels or the WH and ZH production processes to have independent signal strengths. The results are shown in Figures 6.20 and 6.21. In the hypothesis that the true signal strength is the same for all N fitted signal strengths ($N = 2$ for the fit to determine μ_{WH} and μ_{ZH} , and $N = 3$ for the fit with three signal strengths for the three leptonic channels), the difference of the maximum-likelihood estimates of $-2\ln\mathcal{L}$ between the nominal fit (one single μ) and the alternative configurations is expected to

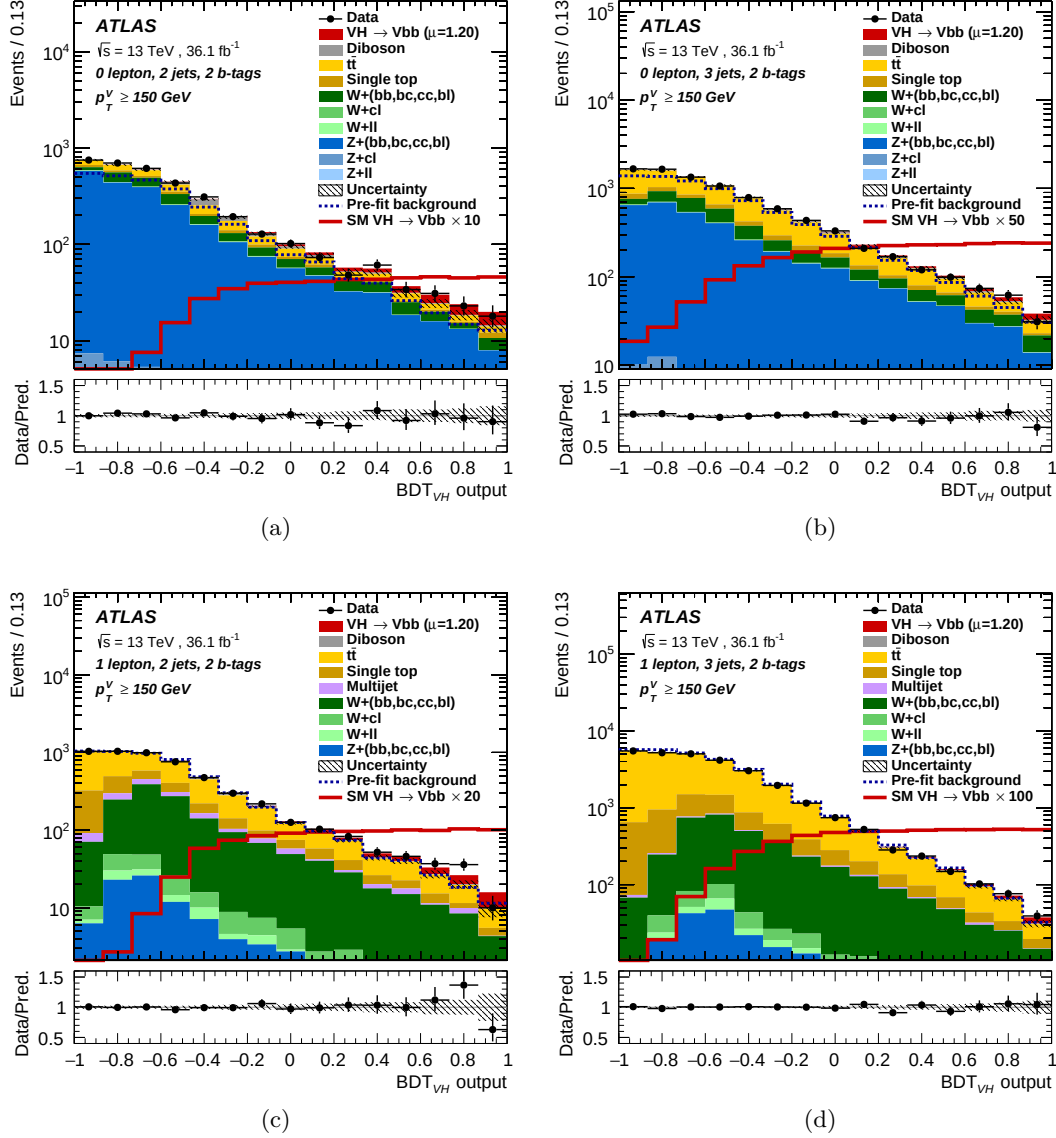


Figure 6.12 – The BDT_{VH} output post-fit distributions in (top) the 0-lepton and (bottom) 1-lepton channels for 2-*b*-tag events, in the (left) 2-jet and (right) 3-jet categories. The background contributions after the global likelihood fit are shown as filled histograms. The Higgs boson signal ($m_H = 125$ GeV) is shown as a filled histogram on top of the fitted backgrounds normalised to the signal yield extracted from data ($\mu = 1.20$), and unstacked as an unfilled histogram, scaled by the factor indicated in the legend. The dashed histogram shows the total background as expected from the pre-fit MC simulation. The size of the combined statistical and systematic uncertainty for the sum of the fitted signal and background is indicated by the hatched band. The ratio of the data to the sum of the fitted signal and background is shown in the lower panel. The BDT_{VH} output distributions are shown with the choice of binning used to define the global likelihood fit.

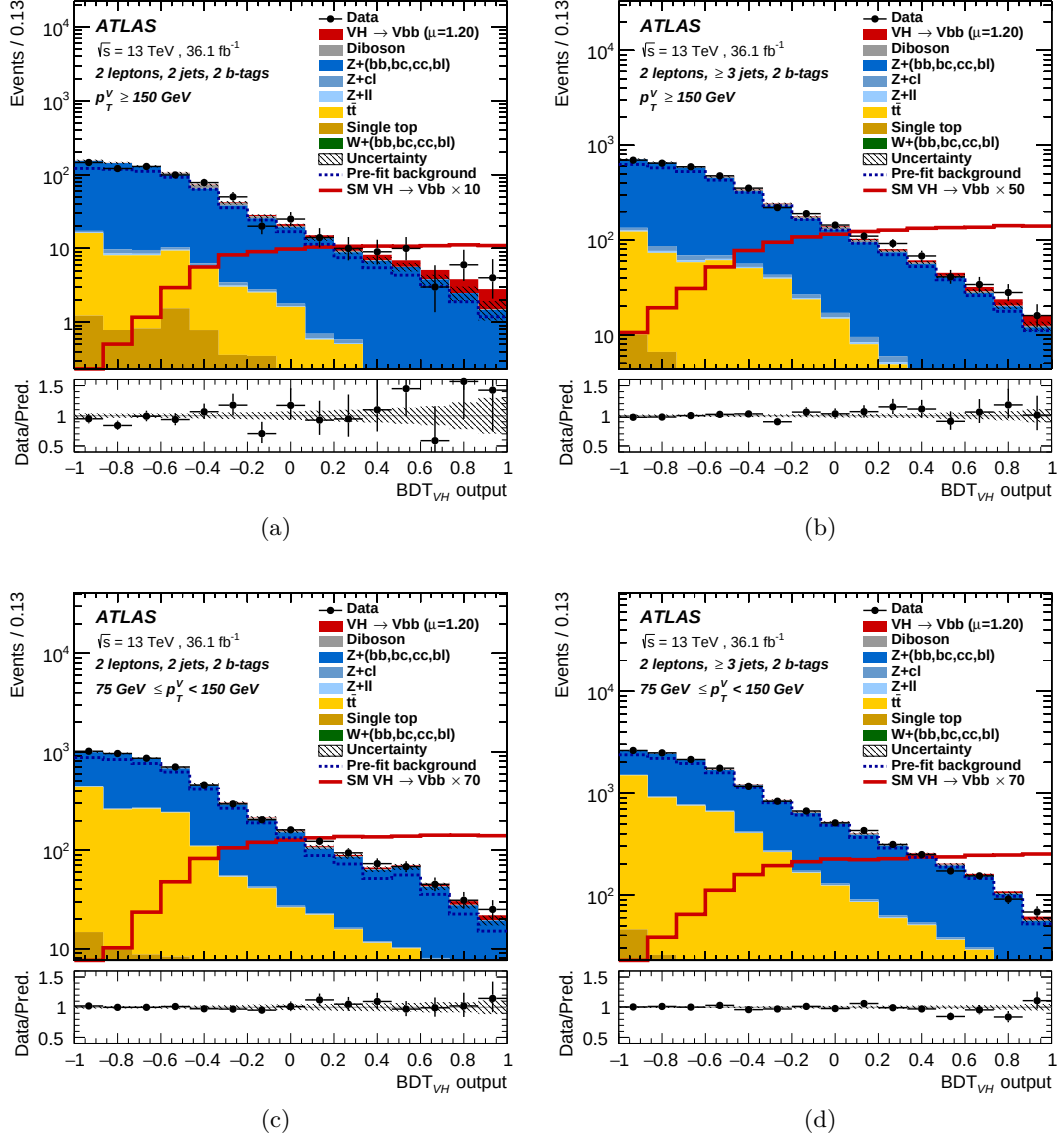


Figure 6.13 – The BDT_{VH} output post-fit distributions in the 2-lepton (top) high p_T^V and (bottom) low p_T^V regions, for 2-b-tag events, in the (left) 2-jet and (right) ≥ 3 jet categories. The background contributions after the global likelihood fit are shown as filled histograms. The Higgs boson signal ($m_H = 125$ GeV) is shown as a filled histogram on top of the fitted backgrounds normalised to the signal yield extracted from data ($\mu = 1.20$), and unstacked as an unfilled histogram, scaled by the factor indicated in the legend. The dashed histogram shows the total background as expected from the pre-fit MC simulation. The size of the combined statistical and systematic uncertainty for the sum of the fitted signal and background is indicated by the hatched band. The ratio of the data to the sum of the fitted signal and background is shown in the lower panel. The BDT_{VH} output distributions are shown with the choice of binning used to define the global likelihood fit.

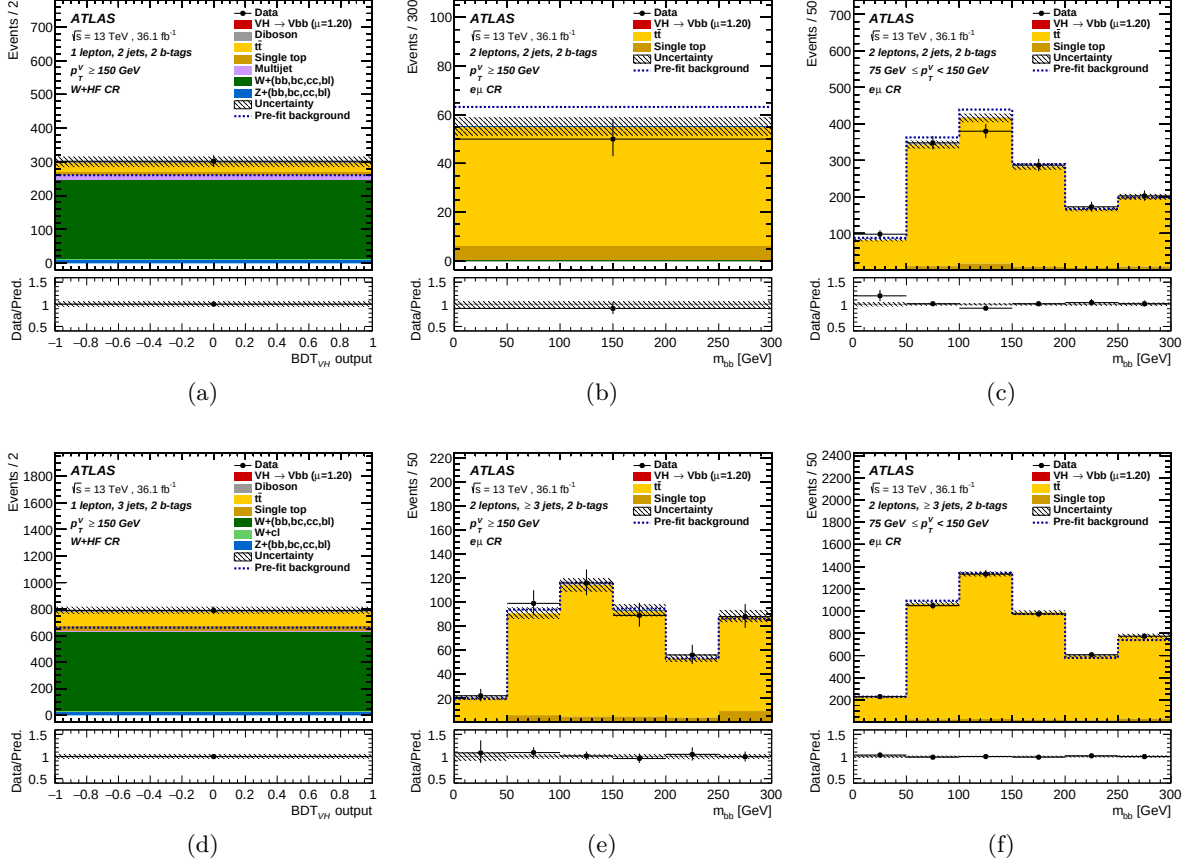


Figure 6.14 – Additional distributions used as input to the global MVA fit: yields in the 1-lepton $W+HF$ (a) 2-jet and (d) 3-jet control regions and in (b) the 2-lepton top $e\mu$ 2-jet, $p_T(V) > 150$ GeV control region; m_{bb} distribution in the 2-lepton top $e\mu$ (e) ≥ 3 -jet, $p_T(V) > 150$ GeV, (c) 2-jet, $75 < p_T(V) < 150$ GeV, (f) ≥ 3 -jet, $75 < p_T(V) < 150$ GeV, control regions. Shown are the data (points with error bars) and expectation (histograms). The background contributions after the global fit are shown as filled histograms. The Higgs boson signal ($m_H = 125$ GeV) is shown as a filled histogram on top of the fitted backgrounds after rescaling the SM cross section according to the value of signal strength extracted from data ($\mu = 1.20$). The dashed histogram shows the total background as expected from the pre-fit MC simulation. The entries in overflow are included in the last bin. The size of the combined statistical and systematic uncertainty for the sum of the signal and fitted background is indicated by the hatched band. The ratio of the data to the sum of the signal and fitted background is shown in the lower panel.

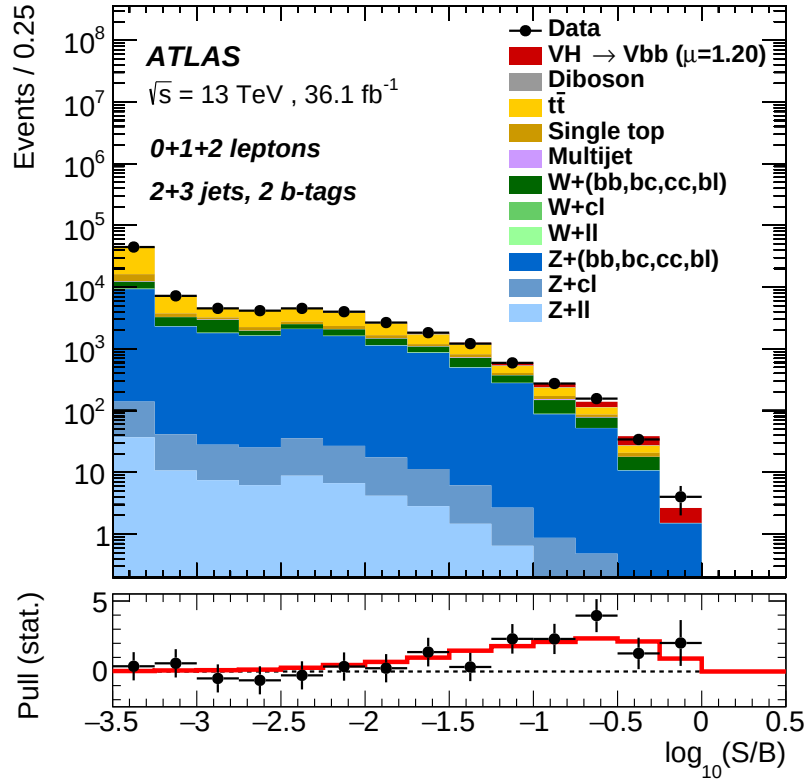


Figure 6.15 – Event yields as a function of $\log(S/B)$ for data, background and a Higgs boson signal with $m_H = 125$ GeV. Final-discriminant bins in all regions are combined into bins of $\log(S/B)$, with the fitted signal being S and the fitted background B . The Higgs boson signal contribution is shown after rescaling the SM cross section according to the value of the signal strength parameter extracted from data ($\mu = 1.20$). The pull (residual divided by its uncertainty) of the data with respect to the background-only prediction is also shown with statistical uncertainties only. The full line indicates the pull of the prediction for signal ($\mu = 1.20$) and background with respect to the background-only prediction.

Table 6.32 – Breakdown of the contributions to the uncertainties in μ . The sum in quadrature of the systematic uncertainties attached to the categories differs from the total systematic uncertainty due to correlations. The b -tagging extrapolation uncertainty refers to the extrapolation of the b -jet calibration above $p_T = 300$ GeV.

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b -tagging	b -jets	0.09
	c -jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
$Z + \text{jets}$		0.07
$W + \text{jets}$		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multi-jet		0.02
MC statistical		0.13

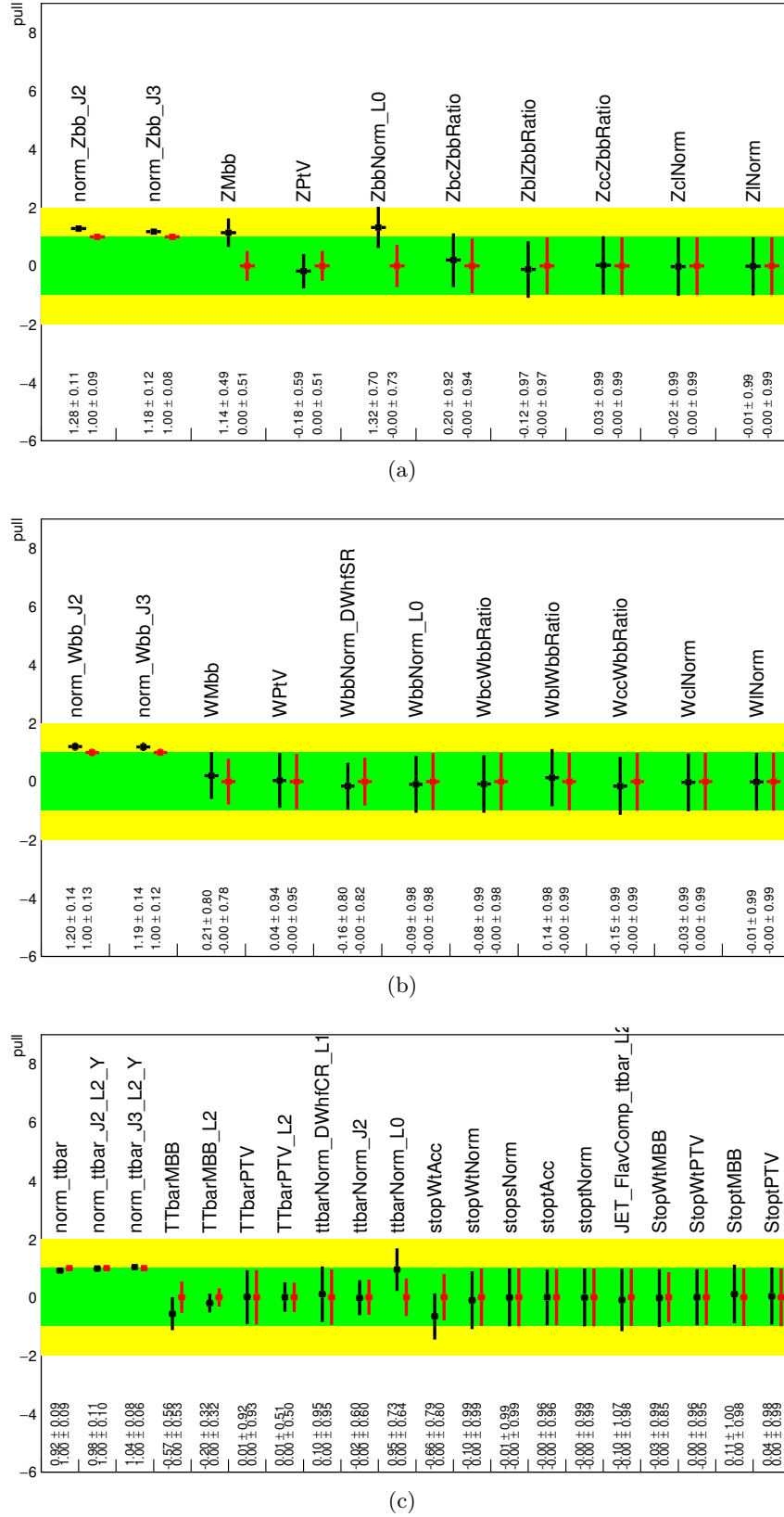


Figure 6.16 – Pull distribution of nuisance parameters associated to the modelling uncertainties of various backgrounds, in the unconditional VH fit: (a) Z +jets, (b) W +jets, (c) top, for the combined unconditional fits performed on Asimov datasets (red) and 2015+2016 data (black).

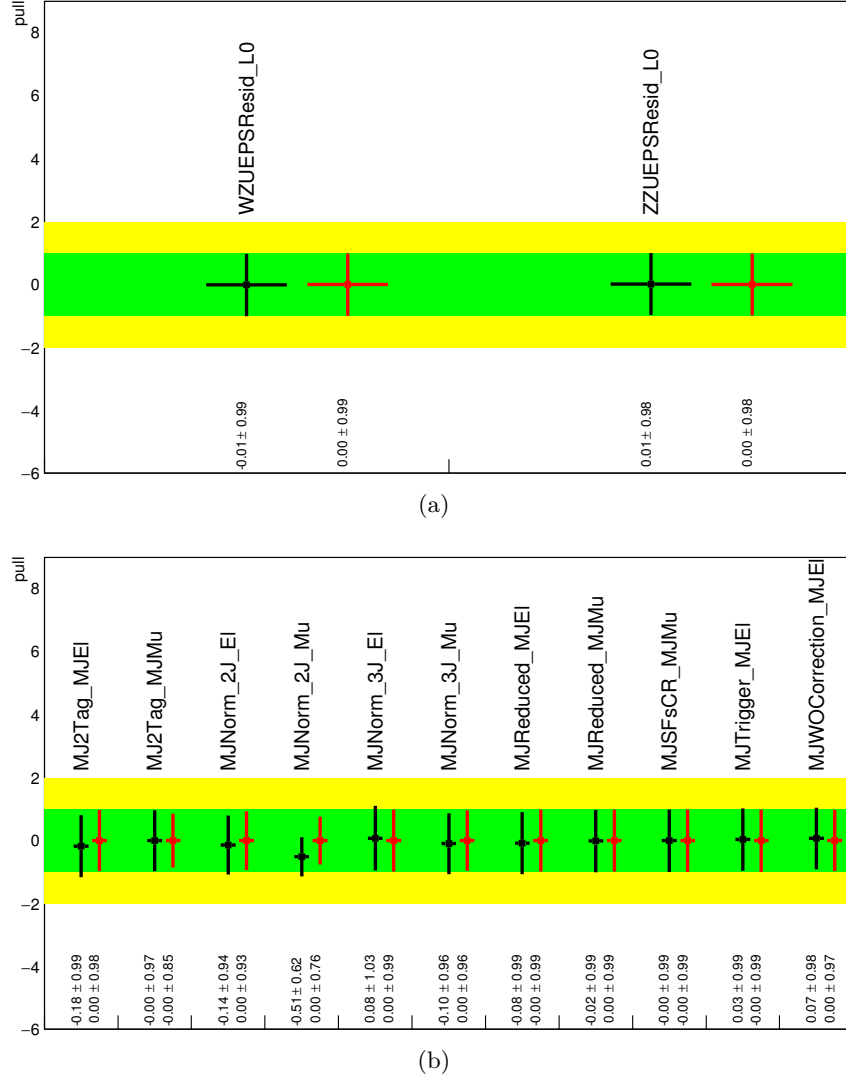


Figure 6.17 – Pull distribution of nuisance parameters associated to the modelling uncertainties of various backgrounds, in the combined unconditional VH fit: (a) diboson, (b) multi-jet, for the combined unconditional fits performed on Asimov datasets (red) and 2015+2016 data (black).

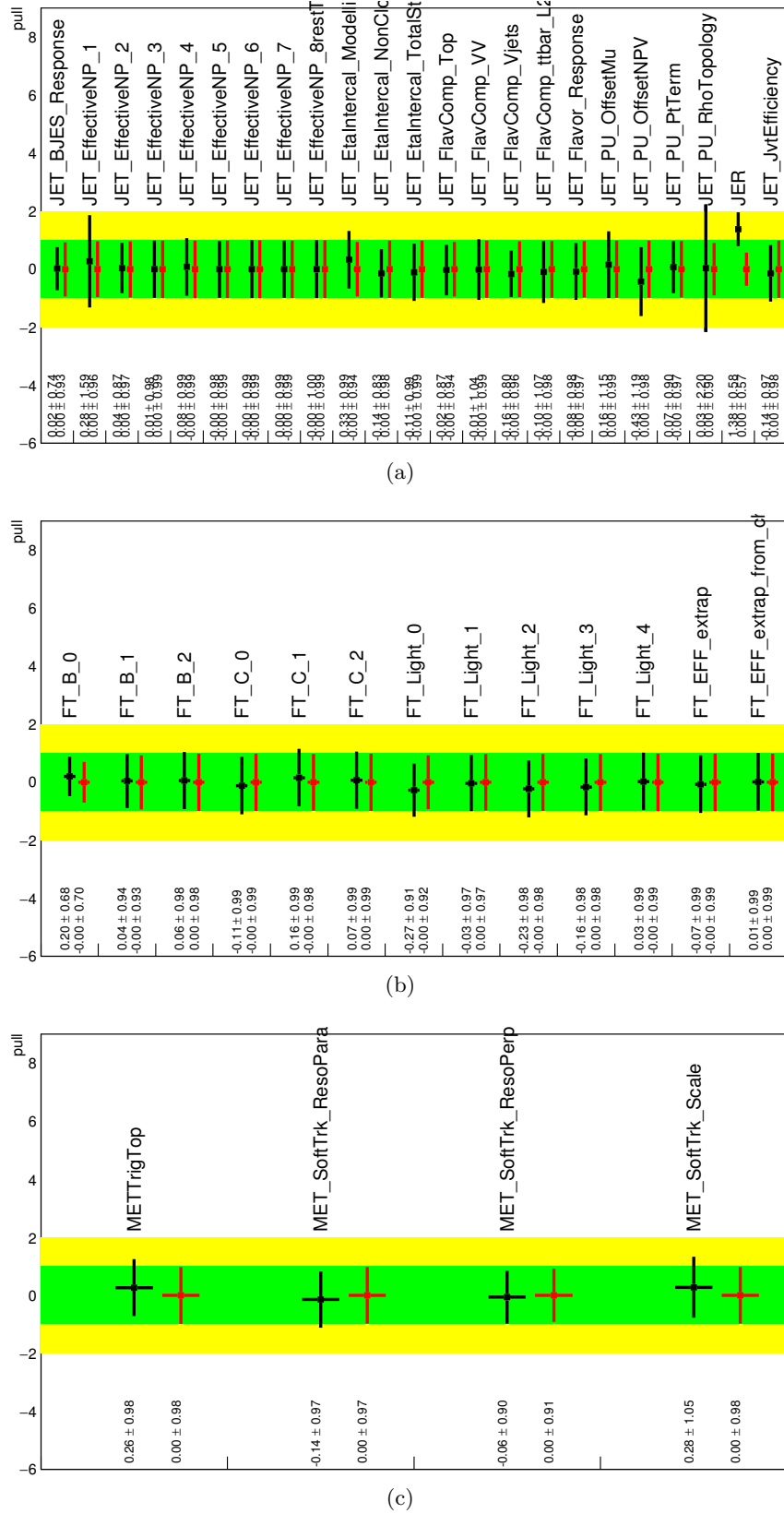
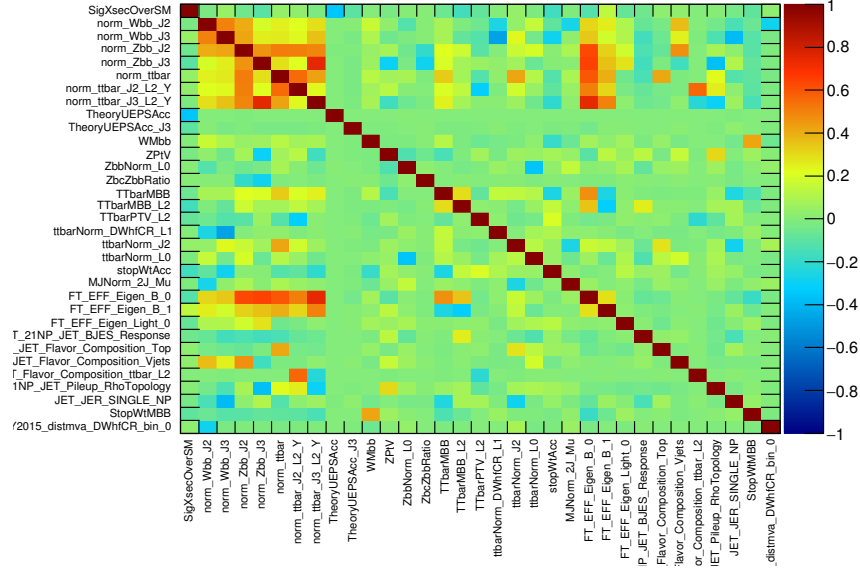
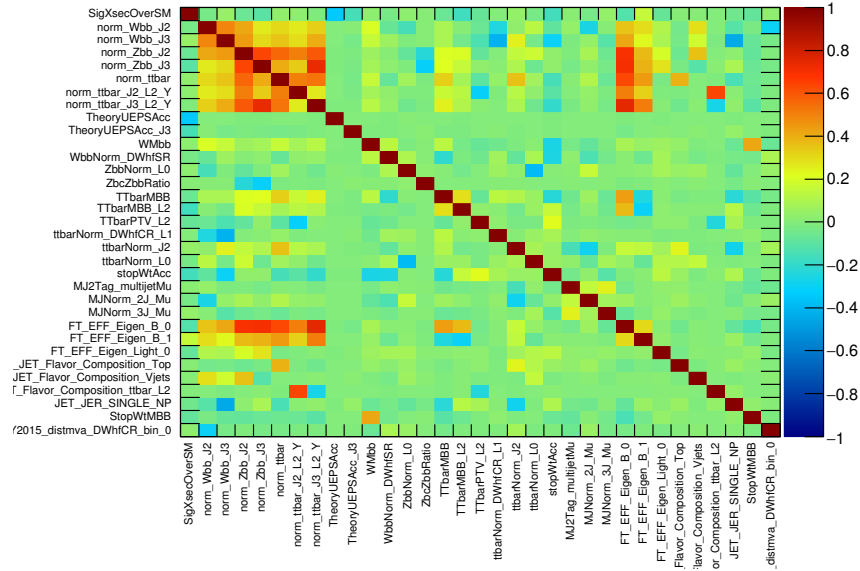


Figure 6.18 – Pull distribution for the NPs associated to the main experimental sources of systematic uncertainties in the unconditional VH fit: (a) jet-related uncertainties, (b) b-tagging, (c) E_T^{miss} , for the combined unconditional fits performed on Asimov datasets (red) and 2015+2016 data (black).



(a)



(b)

Figure 6.19 – Correlation matrices from the unconditional combined VH fit to (a) an Asimov dataset and (b) to 2015 and 2016 data (b).

follow a χ^2 distribution with $N - 1$ degrees of freedom. The corresponding p -value is quoted as a measure of the compatibility of the fitted μ values. The compatibility of the signal strengths in the three lepton channels is 10%; the compatibility of the WH and ZH signal strengths is 75%.

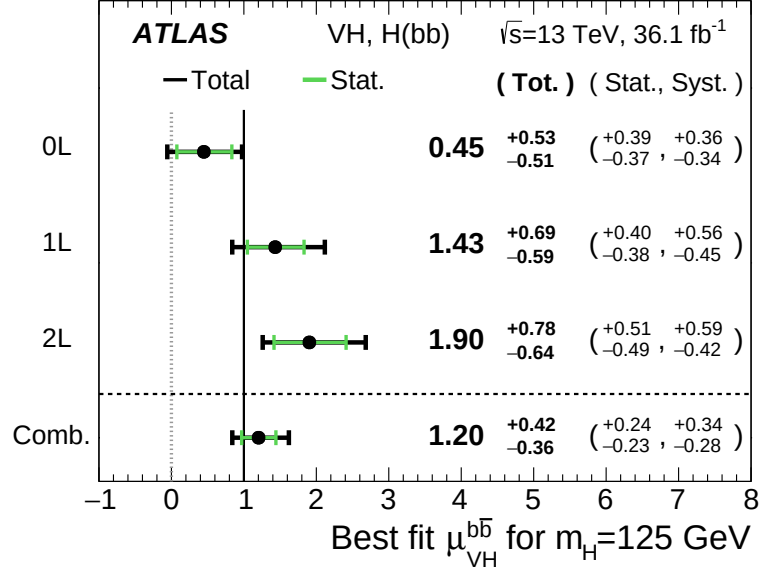


Figure 6.20 – The fitted values of the Higgs boson signal strength for $m_H = 125$ GeV for the 0-, 1- and 2-lepton channels and their combination.

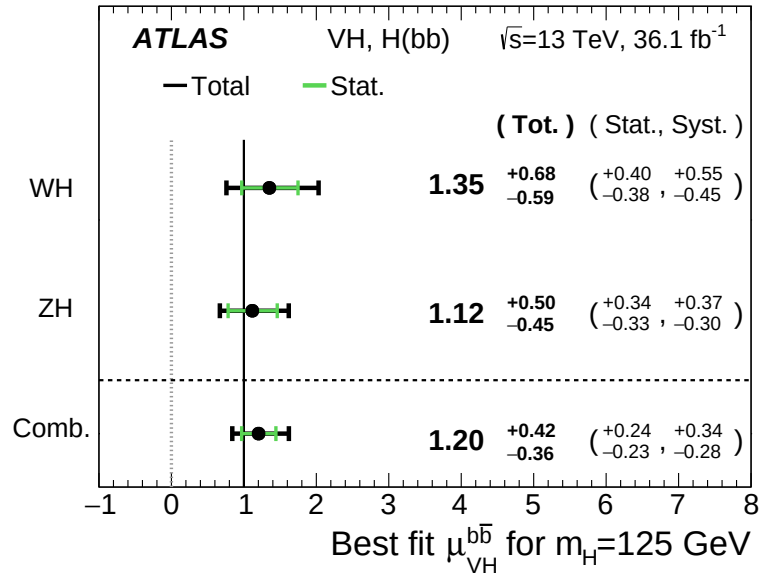


Figure 6.21 – The fitted values of the Higgs boson signal strength for $m_H = 125$ GeV for the WH and ZH processes and their combination.

The WH and ZH production modes are observed with a significance of 2.4 and 2.6 standard deviations, respectively. Using the signal simulation to determine acceptance and correction factors to the full phase space, and removing from the likelihood the theoretical uncertainties for the production cross sections and branching ratio, the fit with two parameters of interest is used to determine the WH and ZH production cross sections times the $H \rightarrow b\bar{b}$ branching ratio:

$$\sigma(WH) \times BR(H \rightarrow b\bar{b}) = 1.08^{+0.54}_{-0.47} \text{ pb}, \quad (6.13)$$

$$\sigma(ZH) \times BR(H \rightarrow b\bar{b}) = 0.57^{+0.26}_{-0.23} \text{ pb}. \quad (6.14)$$

They are in good agreement with the SM predictions of 0.80 pb and 0.51 pb, respectively (the theory uncertainties are negligible with respect to the experimental ones).

The one-POI fit is used instead to determine the sum of the WH and ZH cross sections times the $H \rightarrow b\bar{b}$ branching ratio:

$$\sigma(VH) \times BR(H \rightarrow b\bar{b}) = 1.58^{+0.55}_{-0.47} \text{ pb}, \quad (6.15)$$

in good agreement with the SM expectation of 1.31 pb.

The results of this study are combined with those of the search for the same Higgs boson production and decay mode with 7 and 8 TeV pp collisions [19], by means of a single simultaneous fit to the signal and control regions selected in the 7, 8 and 13 TeV datasets. Before proceeding to the fit, studies were performed to quantify the correlations of the main systematic uncertainties between the two analyses:

- b -tagging efficiency: due to the changes between Run 1 and Run 2 of the ID (with the inclusion of the IBL), of the b -tagging discriminating variable, and of the b -tagging calibration procedure, we assume negligible correlation between the b -tagging efficiency uncertainties of Run 1 and Run 2. We checked that even after correlating the leading b -jet efficiency uncertainties between the two runs only shifted the measured μ by less than 5%, with a negligible effect on its uncertainty.
- jet energy scale: different correlation schemes were tested, with no significant impact on the combined result observed. In the end only b -jet-specific jet energy scale uncertainties were considered correlated between Run 1 and Run 2.
- modelling of the background processes: changes in the centre-of-mass energy, in the event generators used to produce the samples, in the event selection and in the overall ATLAS simulation, reconstruction and analysis framework make it difficult to quantify such correlations. Instead, we estimated the maximum potential shift of the combined signal strength under different hypothetical values of these unknown correlations. To this purpose we performed χ^2 -combinations of the Run 1 and Run 2 μ measurements as a function of different linear correlation coefficients between their uncertainties. Such coefficients were calculated for different values of the correlation coefficients between the Run 1 and Run 2 $t\bar{t}$, Z +HF, and W +HF normalisations and systematic shape variations, taking into account the relative contribution of a specific uncertainty to the total uncertainty for μ . The combined signal strength changes by less than 1%, while its uncertainties varies by at most 4%. For this reason we neglected the correlations between the Run 1 and Run 2 background modelling NPs.

- modelling of the signal: theory uncertainties in the production cross section, in the $H \rightarrow b\bar{b}$ branching ratio, and in the p_T^V -dependent NLO EW corrections, are considered fully correlated between Run 1 and Run 2.

For a Higgs boson mass of 125 GeV, the observed (expected) p_0 of the combined Run 1 and Run 2 data is 0.018% (3×10^{-5}), corresponding to a significance of 3.6 (4.0) standard deviations. The combined signal strength is:

$$\mu = 0.90 \pm 0.18(\text{stat.})^{+0.21}_{-0.19}(\text{syst.}), \quad (6.16)$$

in good agreement with the Standard Model. The overall compatibility of the six measurements (three leptonic channels for each of the two LHC data-taking periods) is 7%. A fit performed with the signal strength floated independently for Run 1 and Run 2 yields a 21% compatibility between the two signal strengths, as shown in Figure 6.22. The signal strengths for the WH and ZH channels are measured to be

$$\mu_{WH} = 1.21^{+0.30}_{-0.29}(\text{stat.})^{+0.34}_{-0.30}(\text{syst.}), \quad (6.17)$$

$$\mu_{ZH} = 0.69^{+0.27}_{-0.26}(\text{stat.})^{+0.23}_{-0.21}(\text{syst.}). \quad (6.18)$$

Figure 6.23 shows the data, background and signal yields as a function of $\log(S/B)$: the excess of the data with respect to the total background is clearly visible in the pull plot of the bottom panel.

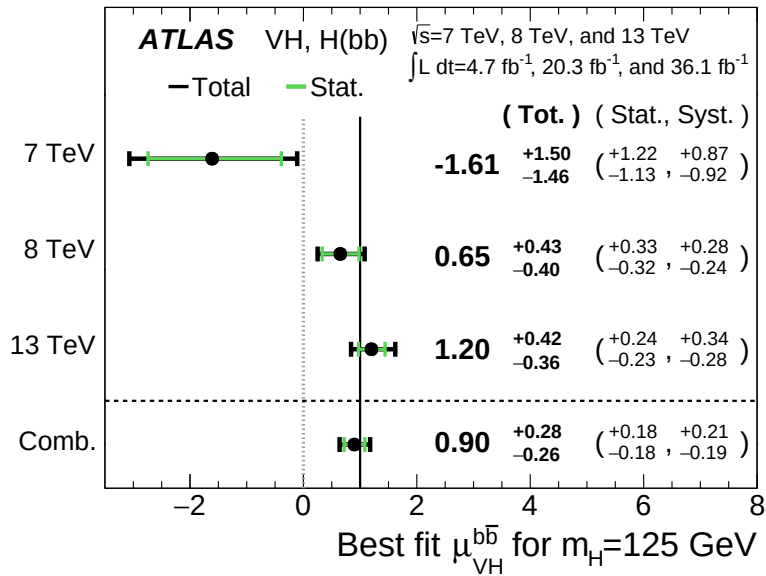


Figure 6.22 – The fitted values of the Higgs boson signal strength parameter μ for $m_H = 125$ GeV separately for the 7 TeV, 8 TeV and 13 TeV datasets and their combination.

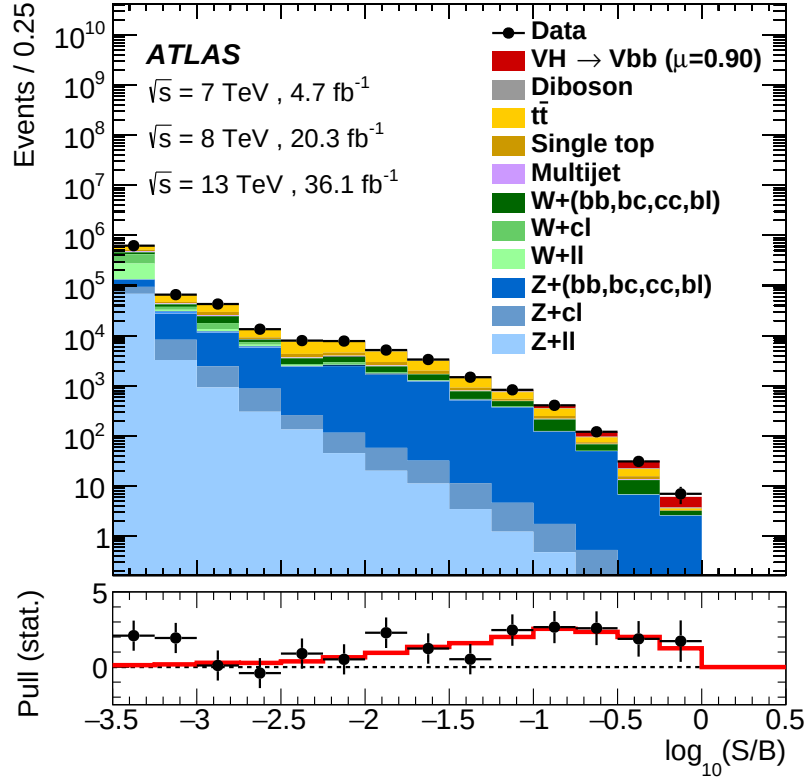


Figure 6.23 – Event yields as a function of $\log(S/B)$ for data, background and Higgs boson signal with $m_H = 125 \text{ GeV}$, for the 7 TeV, 8 TeV and 13 TeV datasets combined. Final-discriminant bins in all regions are combined into bins of $\log(S/B)$, with the fitted signal being S and the fitted background B , for the 7 TeV, 8 TeV and 13 TeV datasets combined. The Higgs boson signal contribution is shown after rescaling the SM cross section according to the value of signal strength extracted from data ($\mu = 0.90$). The pull (residual divided by its uncertainty) of the data with respect to the background-only prediction is also shown with statistical uncertainties only. The full line indicates the pull of the prediction for signal ($\mu = 0.90$) and background with respect to the background-only prediction.

6.11 Cross-check: the diboson analysis

In the diboson analysis, the event selection and classification is the same as in the nominal analysis. The signal under study, however, is the production of diboson VZ , $Z \rightarrow b\bar{b}$ events, instead of VH , $H \rightarrow b\bar{b}$ ones, and its determined from a fit to a dedicated BDT (BDT_{VZ}) which has been trained independently of the BDT_{VH} used in the nominal analysis.

The VZ process has a very similar signature to the VH signal, except mainly for the two- b -jet invariant mass distribution – peaking towards lower values – and the softer p_T spectrum of the two b -jet system. On the other hand, the VZ process has a production cross section which is almost an order of magnitude larger than that of the associated Higgs boson production and its theoretically well known. For these reasons, it provides an important test of the validity of the nominal analysis, if the measured VZ signal strength is in good agreement with one.

As described before, the BDT_{VZ} discriminant uses the same set of input variables and training settings as BDT_{VH} , with two exceptions:

- in the training, the VZ , $Z \rightarrow b\bar{b}$ simulated sample is treated as signal, and all the other simulated samples – including SM VH events with $\mu_{VH} = 1$ – are treated as background.
- since the size of the simulated diboson samples is smaller than that of the VH samples, a coarser binning of the final BDT_{VZ} distribution is adopted to reduce the impact of MC statistical uncertainties, by setting both the parameters z_s and z_b to 5 instead of 10 and 5 as for BDT_{VH} .

In the fit, the parameter of interest is the diboson signal strength μ_{VZ} , which is freely floating. The normalisation uncertainties on the WZ and ZZ processes are thus removed from the likelihood function, while all other systematic uncertainties of the nominal fit are kept. The SM VH , $H \rightarrow b\bar{b}$ process is also included in the fit as a background component, with a nominal signal strength μ_{VH} equal to one and a 50% pre-fit uncertainty.

The measured VZ signal strength is:

$$\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.}), \quad (6.19)$$

in good agreement with the SM prediction. The observed (expected) significance of the VZ signal is 5.8 (5.3) standard deviations. The contribution from each channel is summarised in Table 6.33. Compared to the VH results, the softer $p_T^{b\bar{b}}$ spectrum makes the contribution of the 2-lepton channel more important, being the only one to select events with $p_T^V < 150$ GeV, in the categories with $75 < p_T^V < 150$ GeV. Unlike VH , the significance in the 1-lepton channel is quite poorer than in the 0-lepton and 2-lepton channels. This is attributed to the fact that in the 1-lepton channel the composition of the background is different for the two processes: for VZ , W +HF – which is the least constrained background and has large p_T^V and $m_{b\bar{b}}$ modelling uncertainties – contributes more and $t\bar{t}$ less to the background than for VH .

The signal strengths for the WZ and ZZ channels are measured to be

$$\mu_{WZ} = 1.02 \pm 0.24(\text{stat.})^{+0.55}_{-0.52}(\text{syst.}), \quad (6.20)$$

$$\mu_{ZZ} = 1.13 \pm 0.16(\text{stat.})^{+0.24}_{-0.20}(\text{syst.}), \quad (6.21)$$

in good agreement with the SM and with each other (the compatibility is 88%).

Table 6.33 – The expected and observed p_0 and significance values (in standard deviations) for the individual lepton channels and their combination using 36 fb^{-1} of 13 TeV pp collisions, for the diboson (VZ) signal.

Dataset	Significance	
	Exp.	Obs.
0-lepton	3.6	4.2
1-lepton	1.8	1.7
2-lepton	3.5	3.5
Combined	5.3	5.8

Figure 6.24 shows the data, background and VZ signal yields as a function of $\log(S/B)$.

6.12 Cross-check: the dijet-mass analysis

The dijet-mass analysis consists in extracting the VH signal yield through a fit to the two b -jet invariant mass distribution, after having applied some additional selections on a few other variables used in the BDT_{VH} discriminant. In addition to the requirements of Table 6.3, which are common to the nominal analysis, the requirements of Table 6.34 are also applied.

Table 6.34 – Summary of the event selection criteria in the 0-, 1- and 2-lepton channels for the dijet-mass analysis, applied in addition to those described in Table 6.3 for the multivariate analysis.

Channel			
Selection	0-lepton	1-lepton	2-lepton
m_{T}^W	-	$< 120 \text{ GeV}$	-
$E_{\text{T}}^{\text{miss}}/\sqrt{S_{\text{T}}}$	-	-	$< 3.5\sqrt{\text{GeV}}$

p_{T}^V regions			
p_{T}^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	(200, ∞) GeV
$\Delta R(\mathbf{b}_1, \mathbf{b}_2)$	< 3.0	< 1.8	< 1.2

A maximum ΔR separation between the two b -jets is imposed, decreasing with p_{T}^V as the Higgs boson recoiling against the V boson is more boosted and thus the two b -jets from the Higgs boson decay are closer in space. $\Delta R(\mathbf{b}_1, \mathbf{b}_2)$ is requested to be smaller than 3.0 for $p_{\text{T}}^V \leq 150 \text{ GeV}$, than 1.8 for $150 \text{ GeV} < p_{\text{T}}^V \leq 200 \text{ GeV}$, and than 1.2 for $p_{\text{T}}^V > 200 \text{ GeV}$.

To suppress $t\bar{t}$ background, two different selection criteria are applied in the 1-lepton and 2-lepton channels. In the 1-lepton channel, the W boson transverse mass m_{T}^W is required to be lower than 120 GeV: in $t\bar{t}$ events with two or three reconstructed jets, at least one jet from the hadronic W boson decay contributes to $E_{\text{T}}^{\text{miss}}$, thus increasing the value of m_{T}^W with respect to the WH signal, for which the m_{T}^W distribution has a Jacobian peak near m_W . In the 2-lepton

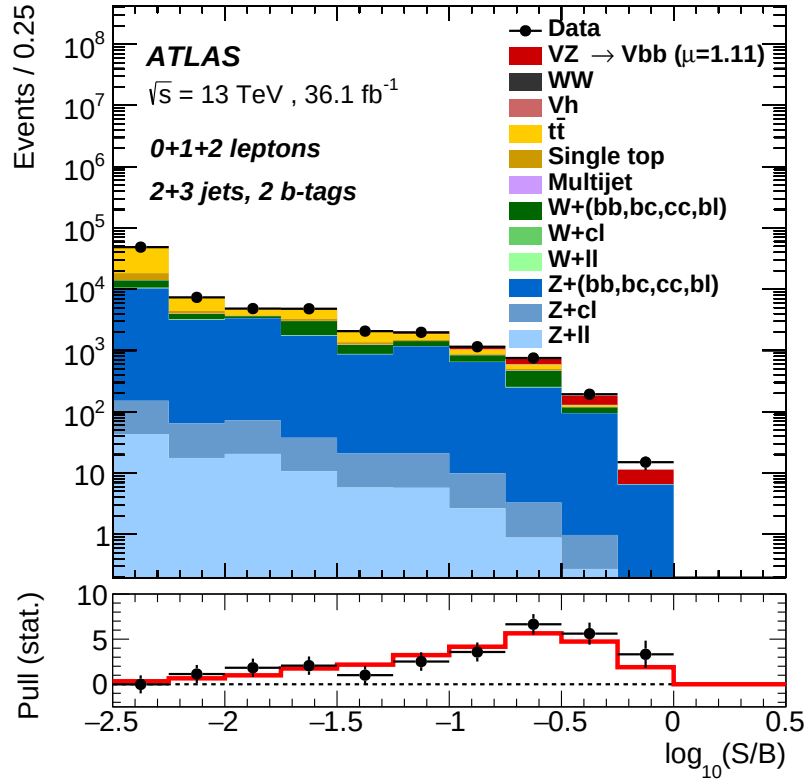


Figure 6.24 – Event yields as a function of $\log(S/B)$ for data, background (including the SM VH production) and VZ signal. Final-discriminant bins in all regions are combined into bins of $\log(S/B)$, with the fitted signal being S and the fitted background B . The VZ contribution is shown after rescaling the SM cross-section according to the value of signal strength extracted from data ($\mu = 1.11$). The pull of the data with respect to the background-only prediction is also shown with statistical uncertainties only. The full line indicates the pull of the prediction for signal ($\mu = 1.11$) and background with respect to the background-only prediction.

channel, in which the signal is expected to produce negligible E_T^{miss} compared to its resolution, unlike $t\bar{t}$ events in which the two neutrinos from the two leptonic W boson decays can produce high E_T^{miss} , the missing transverse momentum significance, defined as the ratio $E_T^{\text{miss}}/\sqrt{S_T}$, where S_T is the scalar sum of the transverse momenta of all jets and leptons in the event, is required to be lower than $3.5\sqrt{\text{GeV}}$.

The signal and control regions used in the fit for the dijet-mass analysis are slightly different than the ones of the nominal analysis, and are summarised in Table 6.35. To increase the sensitivity, the $p_T^V > 150$ GeV signal regions are split in two, $p_T^V > 200$ GeV and $150 < p_T^V < 200$ GeV, leading to a total of fourteen signal regions. To simplify the fit, no dedicated W +HF control region is used, since – after the $t\bar{t}$ background is suppressed by the m_T^W requirement – the low part of the m_{bb} spectrum used in the fit is found to be sufficient to constrain the W +HF background normalisation. The only control regions are the top $e\mu$ ones, defined similarly to the nominal analysis.

Table 6.35 – The distributions used in the global likelihood fit for the dijet-mass analysis, for the signal regions (SR) and control regions (CR), for all the categories in each channel. The two regions marked with * ($\dagger$) are merged into a single region, to reduce statistical uncertainties.

Channel	SR/CR	Categories					
		$75 \text{ GeV} < p_T^V < 150 \text{ GeV}$		$150 \text{ GeV} < p_T^V < 200 \text{ GeV}$		$p_T^V > 200 \text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
1-lepton	SR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2-lepton	SR	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2 lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield*	$m_{bb}^\dagger$	Yield*	$m_{bb}^\dagger$

Figure 6.25 shows the m_{bb} distributions in the dijet-mass analysis for the most sensitive signal regions, the 2-jet, $p_T^V > 200$ GeV ones. Figure 6.26 shows the sum of the m_{bb} distributions of all channels and regions, weighted by their ratio between the fitted Higgs boson signal and background yields, and after subtraction of all backgrounds except for the VZ diboson processes. The data is in good agreement with the sum of the fitted signal and backgrounds.

The fit yields a signal strength of

$$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.}), \quad (6.22)$$

in good agreement with the SM prediction and with the result of the multivariate analysis. The data is in excess of the predicted background with a significance of 3.5 standard deviations, compared to an expected significance – assuming SM VH production cross sections and $BR(H \rightarrow b\bar{b})$ – of 2.8 standard deviations, about 10% lower than the multivariate analysis. The breakdown of the significance provided by each lepton channel is given in Table 6.36. The pattern is similar to that observed in the multivariate analysis.

The breakdown of the systematic uncertainties in the cut-based analysis is given in Table 6.37

A dijet-mass analysis is also used to measure diboson production, as a further cross-check of the multivariate analysis. The VZ signal strength is

$$\mu_{VZ} = 1.01 \pm 0.12(\text{stat.})^{+0.20}_{-0.17}(\text{syst.}), \quad (6.23)$$

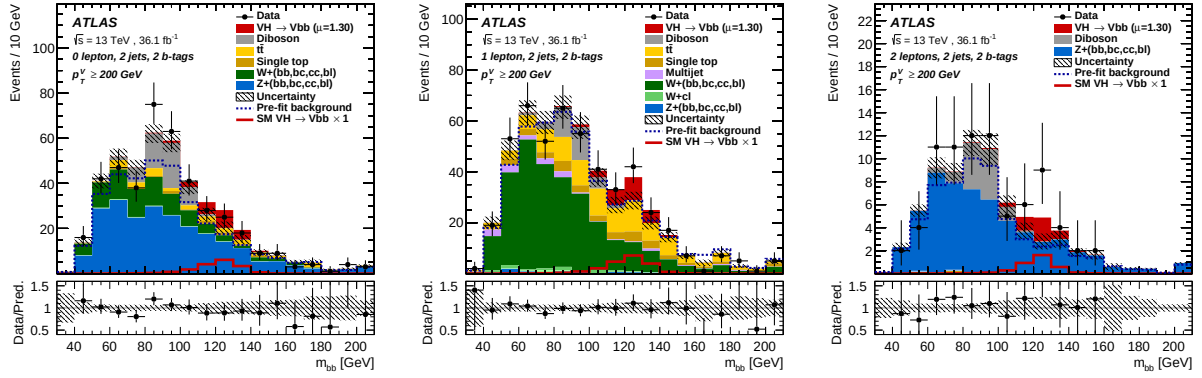


Figure 6.25 – The m_{bb} distributions in the 0-lepton (left), 1-lepton (middle) and 2-lepton (right) channels for 2- b -tag events, in the 2-jet categories for $p_T^V > 200$ GeV. The background contributions after the global likelihood fit are shown as filled histograms. The Higgs boson signal ($m_H = 125$ GeV) is shown as a filled histogram on top of the fitted backgrounds normalised to the signal yield extracted from data ($\mu = 1.30$), and unstacked as an unfilled histogram, scaled by the factor indicated in the legend. The dashed histogram shows the total background as expected from the pre-fit MC simulation. The size of the combined statistical and systematic uncertainty for the sum of the fitted signal and background is indicated by the hatched band. The ratio of the data to the sum of the fitted signal and background is shown in the lower panel.

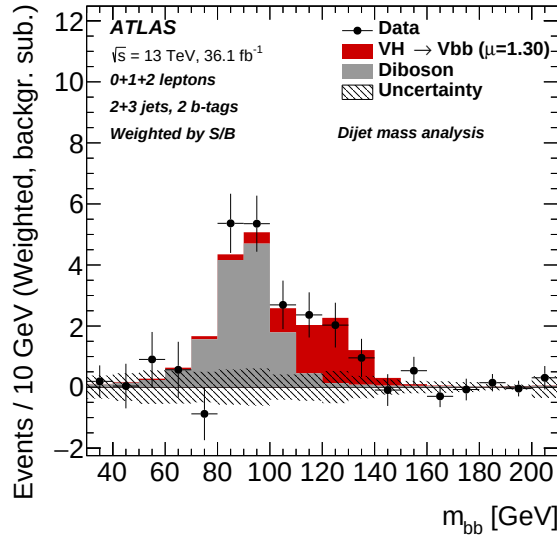


Figure 6.26 – The distribution of m_{bb} in data after subtraction of all backgrounds except for the WZ and ZZ diboson processes, as obtained with the dijet-mass analysis. The contributions from all lepton channels, p_T^V intervals and number-of-jets categories are summed weighted by their respective value of the ratio of fitted Higgs boson signal and background. The expected contribution of the associated WH and ZH production of a SM Higgs boson with $m_H = 125$ GeV is shown scaled by the measured combined signal strength ($\mu = 1.30$). The size of the combined statistical and systematic uncertainty for the fitted background is indicated by the hatched band.

Table 6.36 – The expected and observed p_0 and significance values (in standard deviations) for the individual lepton channels and their combination using 36 fb^{-1} of 13 TeV pp collisions, for the dijet-mass analysis.

Dataset	Significance	
	Exp.	Obs.
0-lepton	1.6	0.4
1-lepton	1.5	2.0
2-lepton	1.6	3.5
Combined	2.8	3.5

Table 6.37 – Breakdown of the contributions to the uncertainties in μ in the cut-based analysis.

Source of uncertainty	σ_μ
Total	0.43
Statistical	0.27
Systematic	0.33
Experimental uncertainties	
Jets, E_T^{miss}	0.06
Leptons	0.01
b -tagging	0.08
Pile-up	0.01
Luminosity	0.03
Theoretical and modelling uncertainties	
Signal	0.18
Floating normalisations	0.07
$Z + \text{jets}$	0.06
$W + \text{jets}$	0.06
$t\bar{t}$	0.09
Single top quark	0.05
Diboson	0.05
Multi-jet	0.02
MC statistical	0.15

in good agreement with the Standard Model prediction and with the result of the multivariate diboson analysis.

Chapter 7

Observation of VH production and $H \rightarrow b\bar{b}$ decays, and future prospects

In summer 2018, at the ICHEP 2018 conference, the ATLAS Collaboration has presented the results of the VH , $H \rightarrow b\bar{b}$ search with 80 fb^{-1} of Run 2 data, leading to the observation of VH production and of $H \rightarrow b\bar{b}$ decays. The first section of this chapter will present the small differences between the study presented at the ICHEP 2018 conference and the EPS 2017 analysis described in the previous chapter, some details about the combination with the other VH production and $H \rightarrow b\bar{b}$ decay searches, and the results of such combinations.

A few weeks after ICHEP 2018, in August 2018, the CMS Collaboration has also presented its latest results on the VH , $H \rightarrow b\bar{b}$ search [25], based on a similar amount of data as that analysed by ATLAS. An excess of events with a significance of 3.3σ over the SM background is observed in the 13 TeV data collected in 2017. Combined with previous results at 7, 8 and 13 TeV, the observed significance for this production and decay mode is 4.8σ , and the corresponding signal strength is 1.01 ± 0.22 . A combination with the other CMS searches for $H \rightarrow b\bar{b}$ yields an observed (expected) significance of 5.6 (5.5) standard deviations and a signal strength of 1.04 ± 0.20 . The results provide an independent confirmation of the Standard Model Higgs boson predictions and of the results obtained by the ATLAS Collaboration. Some details about this result are given in the second section of this chapter.

The third section of the chapter is devoted to a measurement, not yet published, of a reduced set of the so-called “stage-1” simplified template cross sections of the VH production mode using $H \rightarrow b\bar{b}$ decays, based on the ATLAS data analysed for the $H \rightarrow b\bar{b}$ observation presented in ICHEP 2018. A brief introduction to the simplified template cross section framework will also be given.

Finally, the last section of this chapter contains the results of perspective studies performed to estimate the ultimate sensitivity to VH , $H \rightarrow b\bar{b}$ production with an upgraded ATLAS detector at the high-luminosity LHC, performed in the context of the update of the European particle physics strategy that will take place in 2019.

7.1 Analysis of 2017 data and observation of $H \rightarrow b\bar{b}$ decays and of VH production

In summer 2018 the ATLAS Collaboration has presented an updated measurement of the VH , $H \rightarrow b\bar{b}$ cross section, and a combination with the results of other $H \rightarrow b\bar{b}$ decays or VH

production mode studies. Preliminary results were shown at the ICHEP 2018 conference [100], and recently published Physics Letters B [24].

Compared to the results presented in the previous chapter, a larger data sample has been analysed, corresponding to about 80 fb^{-1} of 13 TeV pp collisions collected in 2015–2017, more than doubling the integrated luminosity of the previous study. In addition, enhancements were introduced in the analysis to reduce the impact of the systematic uncertainties, and larger samples of simulated events were used to model the background processes, in order to reduce the size of the “MC statistical” uncertainty of Table 6.32.

The MC samples – with sizes between 2.25 and 2.8 times larger than those used in the “EPS 2017” analysis – were generated to simulate the data taking conditions of the full 2015–2017 data sample. The MC event generators used are similar to those of the previous analysis, with some updates to exploit recent technical developments in some of such programs: single-top samples are produced with POWHEG-BOX v2 instead of POWHEG-BOX v1, interfaced to PYTHIA 8 instead of PYTHIA 6 for the modelling of underlying event, parton shower and hadronisation. The PDF set used for the generation of the WW sample is NNPDF 3.0 (CT10 in the previous analysis), consistently with all the other background samples. In addition to the quark induced diboson samples, semi-leptonic loop-induced $gg \rightarrow VV$ samples were also generated, using SHERPA 2.2.2 with the NNPDF 3.0 NNLO PDF set. These samples use LO accurate matrix elements for the $VV + 0$ parton and $VV + 1$ parton final states.

Both data and simulation were reconstructed with a new version of (release 21) of the ATLAS reconstruction software, with improved reconstruction, identification and calibration algorithms for lepton, jets, b -jets and $E_{\text{T}}^{\text{miss}}$, and efficiencies and resolutions determined with larger data control samples collected until the end of 2017. The analysis strategy itself, including the selection, the event categories, the fit strategy to determine signal and background yields, the BDT input variables and training settings, and the evaluation of systematic uncertainties, was left unchanged. However, the BDT in each category was retrained using the latest available simulation samples, and systematic uncertainties were recomputed based on the uncertainties on the latest calibrations and using the newest MC samples.

Concerning the systematic uncertainties, the main changes are the following:

- the uncertainty on the luminosity itself, exploiting the larger size of the samples used for its measurement, is reduced from 3.2% to 2.0%.
- Other experimental uncertainties exploit the latest calibrations, performed with twice larger control samples than those used for the EPS 2017 results;
- Modelling uncertainties were recomputed and found to be largely similar to those used for the previous round of analysis; for simplicity, the same numbers for the EPS 2017 results were used for most of the modelling uncertainties;
- An important exception is the systematic uncertainty from the parton shower and underlying event modelling in signal simulated samples. After the EPS 2017 results were published, a bug was discovered in the calculation of the sum of event weights in the alternative MC samples used to estimate this uncertainty, leading to an inflated estimate of the systematic uncertainty when comparing the acceptance between the nominal and alternative signal samples. In addition, an extra contribution to the parton-shower uncertainty

was determined by looking at the variation in signal acceptance induced by the variations of the AZNLO parton shower tune. After fixing the bug, and using the larger simulated samples produced for the analysis presented in this section and the new approach to estimate this uncertainty, the underlying event and parton shower uncertainties were typically reduced from 10–14% to 2–6%.

- A second exception is represented by Wt single-top events, for which a more refined modelling strategy has been implemented, taking into account the flavour composition of the events. In events where the two b -tagged jets are b -flavoured ($Wt \rightarrow b\bar{b}$), the comparison between the DR and DS schemes is the dominant source of systematic uncertainty. In events where at most one of the b -tagged jets is b -flavoured ($Wt \rightarrow other$), the dominant source of systematic uncertainty is from a combination of the comparisons between samples generated with different ME calculators or parton showers. Such differences are due to the different topologies of selected candidates, where $Wt \rightarrow b\bar{b}$ mostly select one b -jet from the top and one from the W decay, while $Wt \rightarrow other$ often selects both jets from the top quark decay chain. For this reason, modelling uncertainties were computed and treated separately for these two different processes.

The acceptance of the selection for signal events is summarised in Table 7.1.

Table 7.1 – The VH signal cross section times branching ratio and acceptance in the three channels for data collected at $\sqrt{s} = 13$ TeV in 2015–2017. The qq - and gg -initiated ZH processes are shown separately. The branching ratios are calculated considering only decays to muons and electrons for $Z \rightarrow \ell\ell$, decays to all three lepton flavours for $W \rightarrow \ell\nu$ and decays to all neutrino flavours for $Z \rightarrow \nu\nu$. The acceptance is calculated as the fraction of events remaining in the combined signal and control regions after the full event selection.

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	$\sigma \times BR$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	29.9	< 0.1	0.1	6.0
$gg \rightarrow ZH \rightarrow \ell\ell b\bar{b}$	4.8	< 0.1	0.2	13.5
$qq \rightarrow WH \rightarrow \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \rightarrow ZH \rightarrow \nu\nu b\bar{b}$	14.3	3.5	–	–

A fit to the signal regions and control regions is performed, yielding a signal strength value in good agreement with the SM prediction of 1:

$$\mu = 1.16^{+0.16}_{-0.16}(\text{stat.})^{+0.21}_{-0.19}(\text{syst.}), \quad (7.1)$$

Compared to the previous measurement, the statistical uncertainty is reduced by a factor 1.5 due to the twice larger sample. Systematic uncertainties are also reduced by a similar factor due to important reductions of the MC statistical uncertainty and floating normalisations (almost halved), the signal uncertainty (down by a factor 1.8 largely due to the reduced underlying event and parton shower uncertainty), as well as the improved b -tagging efficiency calibration of b and

light jets and the reduced luminosity uncertainty. The contribution of each group of sources of systematic uncertainties to the total uncertainty is summarised in Table 7.2.

Table 7.2 – Breakdown of the contributions to the uncertainties in μ in the VH , $H \rightarrow b\bar{b}$ measurement based on 80 fb^{-1} of 13 TeV pp collisions. The sum in quadrature of the systematic uncertainties attached to the categories differs from the total systematic uncertainty due to correlations. The b -tagging extrapolation uncertainty refers to the extrapolation of the b -jet calibration above $p_T = 300 \text{ GeV}$.

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b -tagging	b -jets	0.061
	c -jets	0.042
	light jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
$Z + \text{jets}$		0.055
$W + \text{jets}$		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

The fitted values of the background scale factors that are freely floating in the fit are summarized in Table 7.3. They agree with the previous estimates and with the SM predictions within their uncertainties; the only large deviation being observed for the Z +HF scale factor (1.37 ± 0.11) in the 2-jet category.

Figure 7.1 shows the data, background and signal yields of the eight signal regions grouped together as a function of $\log(S/B)$, where S and B are the fitted signal and background yields, respectively. Good agreement between the data and the fit projection can be observed.

Table 7.3 – Factors applied to the nominal normalisations of the $t\bar{t}$, W +HF, and Z +HF backgrounds, as obtained from the global fit to the 13 TeV data for the nominal multivariate analysis, used to extract the Higgs boson signal. The errors include the statistical and systematic uncertainties.

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
W +HF 2-jet	1.19 ± 0.12
W +HF 3-jet	1.05 ± 0.12
Z +HF 2-jet	1.37 ± 0.11
Z +HF 3-jet	1.09 ± 0.09

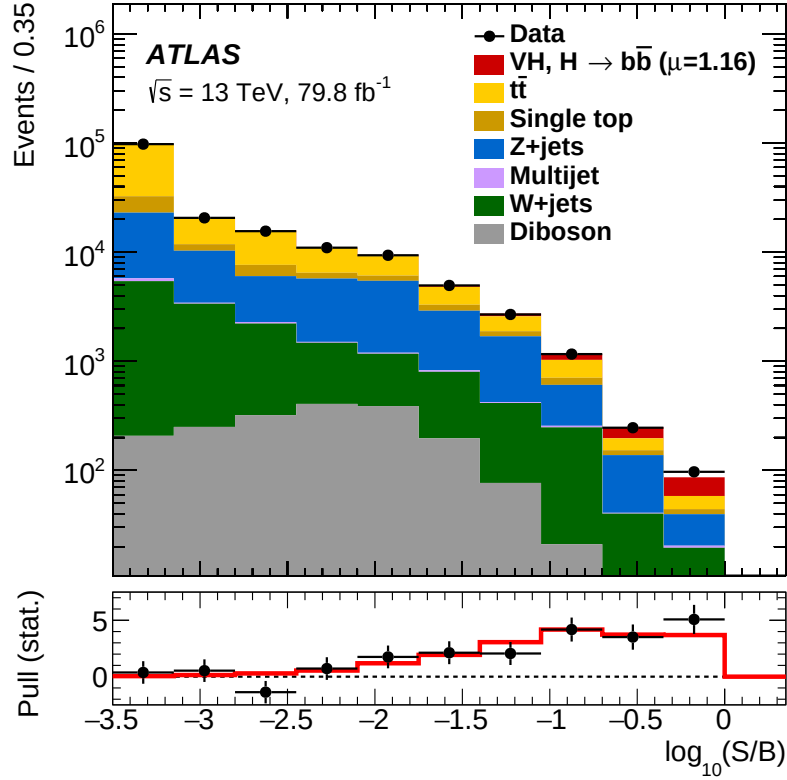


Figure 7.1 – Event yields as a function of $\log(S/B)$ for data, background and a Higgs boson signal with $m_H = 125$ GeV, in the analysis of 80 fb^{-1} of 13 TeV pp collisions. Final-discriminant bins in all regions are combined into bins of $\log(S/B)$, with the fitted signal being S and the fitted background B . The Higgs boson signal contribution is shown after rescaling the SM cross section according to the value of the signal strength parameter extracted from data ($\mu = 1.16$). The pull (residual divided by its uncertainty) of the data with respect to the background-only prediction is also shown with statistical uncertainties only. The full line indicates the pull of the prediction for signal ($\mu = 1.16$) and background with respect to the background-only prediction.

For a Higgs boson mass of 125 GeV the p_0 of the data is 5.3×10^{-7} , corresponding to a significance of 4.9 standard deviations, close to the conventional 5σ threshold used in particle physics to claim an observation. The expected p_0 , when the backgrounds are normalised to the values obtained from the fit to the data, is 7.3×10^{-6} , corresponding to an expected significance of 4.3σ . The contribution to the observed and expected significance from each channel is shown in Table 7.4.

Table 7.4 – The expected and observed p_0 and significance values (in standard deviations) for the individual lepton channels and their combination using 80 fb^{-1} of 13 TeV pp collisions. The expected values are evaluated assuming a SM Higgs boson with a mass of 125 GeV.

Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
Combined	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

The fit is repeated by allowing the WH and ZH production processes to have independent signal strengths. The results are shown in Figure 7.2. Both signal strengths are in good agreement with the SM predicted value of one. The compatibility of the signal strengths of the WH and ZH signal strengths is 84%.

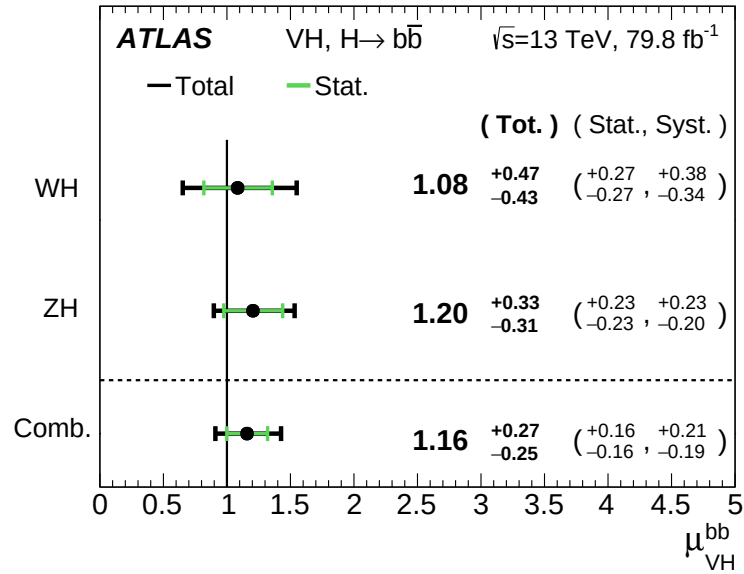


Figure 7.2 – The fitted values of the Higgs boson signal strength for $m_H = 125 \text{ GeV}$ for the WH and ZH processes and their combination, in the analysis of 80 fb^{-1} of 13 TeV pp collisions.

The same cross-checks as in the EPS 2017 analysis, namely the dijet-mass analysis and the diboson analysis, are performed. The dijet-mass analysis yields a signal strength of

$$\mu = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.}), \quad (7.2)$$

in good agreement with the result of the multivariate analysis. The observed excess has a significance of 3.6 standard deviations, compared to an expectation of 3.5 standard deviations. Figure 7.3 shows the sum of the m_{bb} distributions of all channels and regions, weighted by their ratio between the fitted Higgs boson signal and background yields, and after subtraction of all backgrounds except for the VZ diboson processes. The data is in good agreement with the sum of the fitted signal and backgrounds.

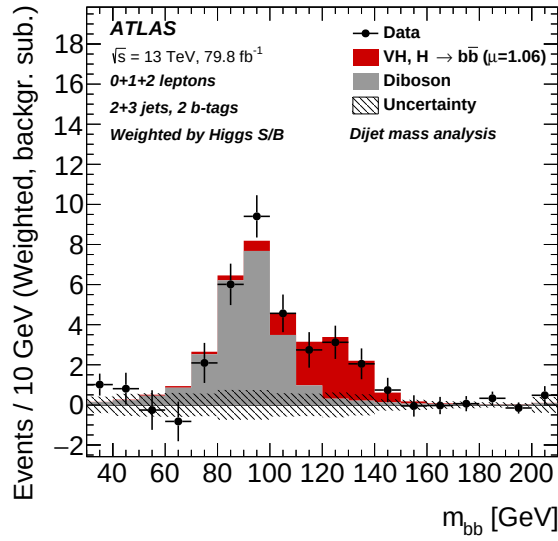


Figure 7.3 – The distribution of m_{bb} in data after subtraction of all backgrounds except for the WZ and ZZ diboson processes, as obtained with the dijet-mass analysis of 80 fb $^{-1}$ of 13 TeV pp collisions. The contributions from all lepton channels, p_T^V intervals and number-of-jets categories are summed weighted by their respective value of the ratio of fitted Higgs boson signal and background. The expected contribution of the associated WH and ZH production of a SM Higgs boson with $m_H = 125$ GeV is shown scaled by the measured combined signal strength ($\mu = 1.06$). The size of the combined statistical and systematic uncertainty for the fitted background is indicated by the hatched band.

The diboson analysis yields a VZ signal strength of:

$$\mu_{VZ} = 1.20 \pm 0.08(\text{stat.})^{+0.19}_{-0.16}(\text{syst.}), \quad (7.3)$$

in good agreement with the SM prediction. Analogously to the VH signal, fits are also performed with separate signal strengths for the WZ and ZZ production modes, leading to the following results

$$\mu_{WZ} = 0.90 \pm 0.17(\text{stat.})^{+0.43}_{-0.41}(\text{syst.}), \quad (7.4)$$

$$\mu_{ZZ} = 1.26 \pm 0.10(\text{stat.})^{+0.20}_{-0.17}(\text{syst.}), \quad (7.5)$$

in good agreement with the SM and with each other (the compatibility is 47%).

A combination with the result of the Run 1 VH , $H \rightarrow b\bar{b}$ search, similarly to what described in Section 6.10 was performed, leading to the following measurement of the VH , $H \rightarrow b\bar{b}$ signal strength:

$$\mu = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.}), \quad (7.6)$$

in excellent agreement with SM predictions. The significance of the excess corresponding to the signal is of 4.9 standard deviations, compared with an expectation of 5.1 standard deviations. The WH and ZH , $H \rightarrow b\bar{b}$ signal strengths are in good agreement with each other (72% compatibility) and with the SM prediction, as shown in Figure 7.4.

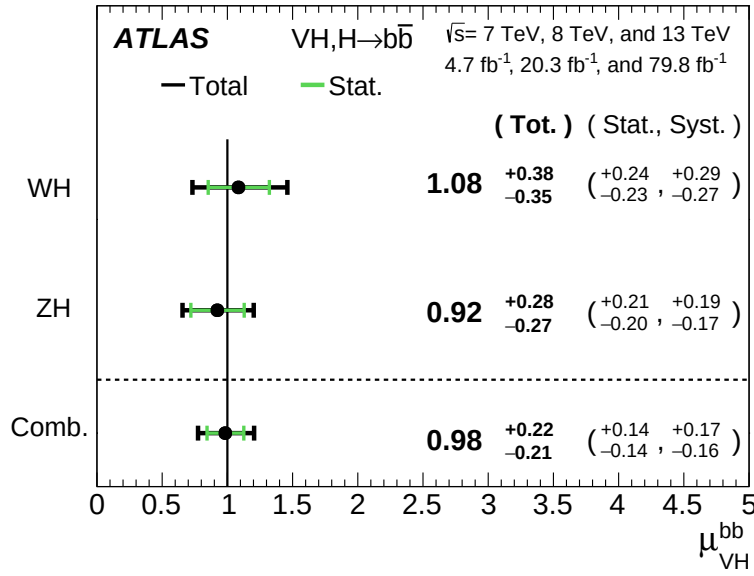


Figure 7.4 – The fitted values of the Higgs boson signal strength for $m_H = 125$ GeV for the WH and ZH processes and their combination, using the 7 TeV, 8 TeV and 13 TeV (80 fb $^{-1}$) data.

This result is further combined with those of the searches for the Standard Model Higgs boson decays to $b\bar{b}$ with other production modes (association with a $t\bar{t}$ pair and in vector-boson fusion), using both Run 1 and Run 2 data. Assuming that the ratios of the cross sections of various production modes are as predicted by the SM, the observed (expected) significance of the $H \rightarrow b\bar{b}$ decay is 5.4 (5.5) standard deviations, yielding to the observation of this decay. Assuming further that the production cross sections themselves are those predicted by the SM, the signal strength for the $H \rightarrow b\bar{b}$ branching ratio is determined:

$$\mu_{H \rightarrow b\bar{b}} = 1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.}). \quad (7.7)$$

The contribution from each channel to the significance of the excess is shown in Table 7.5. The signal strength for $\mu_{H \rightarrow b\bar{b}}$ of the three production modes is shown in Figure 7.5.

Finally, the result of the Run 2 VH , $H \rightarrow b\bar{b}$ search is combined with those of the other searches with the same dataset of VH production, based on $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decays. Assuming SM predictions for the relative branching ratios of the three decay modes leads to an observed (expected) significance of the excess with respect to the background of 5.3 (4.9) standard deviations. Most of the significance comes from the $b\bar{b}$ decay (4.9 σ), with the other

Table 7.5 – Expected and observed significance values (in standard deviations) for the $H \rightarrow b\bar{b}$ channels fitted independently and their combination using the 7 TeV, 8 TeV and 13 TeV data.

Channel	Significance	
	Exp.	Obs.
VBF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
Combined	5.5	5.4

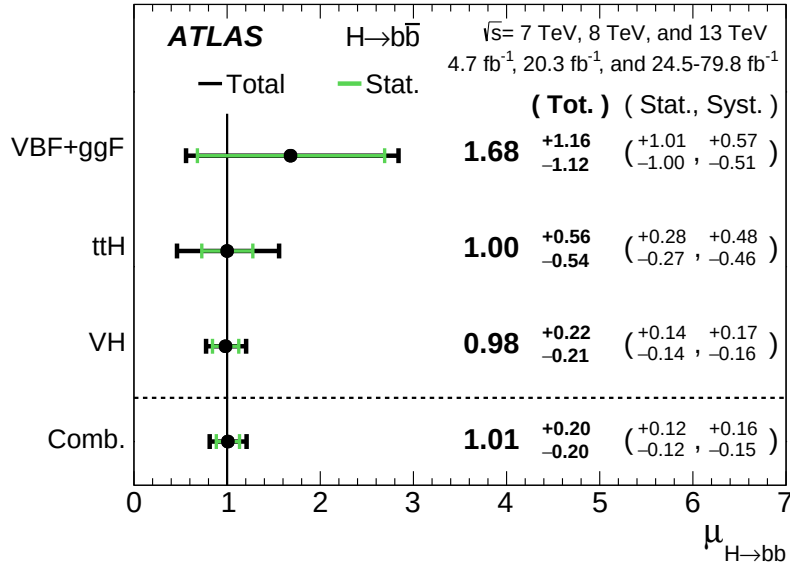


Figure 7.5 – The fitted values of the Higgs boson signal strength $\mu_{H \rightarrow b\bar{b}}$ for $m_H = 125$ GeV separately for the VH , $t\bar{t}H$ and VBF analyses along with their combination, using the 7 TeV, 8 TeV and 13 TeV data. The individual $\mu_{H \rightarrow b\bar{b}}$ values for the different production modes are obtained from a simultaneous fit with the signal strengths for each of the processes floating independently. The probability of compatibility of the individual signal strengths is 83%. The VBF analysis is labelled as VBF+ggF since a significant contamination from gluon fusion production is expected.

two channels contributing an extra 1.1σ ($H \rightarrow ZZ^* \rightarrow 4\ell$) and 1.9σ ($H \rightarrow \gamma\gamma$). Assuming SM branching ratios to the three decay channels, the signal strength for μ_{VH} is measured:

$$\mu_{VH} = 1.13 \pm 0.15(\text{stat.})^{+0.18}_{-0.17}(\text{syst.}). \quad (7.8)$$

The signal strength for each of the three decay modes is shown in Figure 7.6. Thanks to this result also the VH production mode is now established, as it was already the case for gluon fusion, VBF and $t\bar{t}H$.

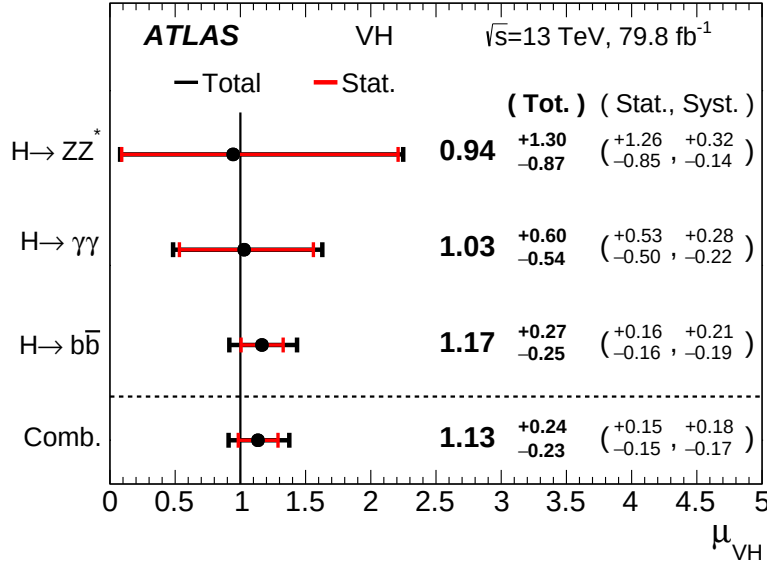


Figure 7.6 – The fitted values of the Higgs boson signal strength μ_{VH} for $m_H = 125$ GeV separately for the $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay modes, along with their combination, using 80 fb^{-1} of 13 TeV data. The individual μ_{VH} values for the different decay modes are obtained from a simultaneous fit with the signal strengths for each of the processes floating independently. The probability of compatibility of the individual signal strengths is 96%.

7.2 Observation of $H \rightarrow b\bar{b}$ decays by the CMS Collaboration

Soon after ATLAS observation of the $H \rightarrow b\bar{b}$ decay documented in Ref. [100], the CMS Collaboration released an article on the observation, with a similar amount of data, of the same Higgs boson decay; the article was recently published in Physical Review Letters [25].

Similarly to ATLAS, the observation is obtained through the combination of the results of searches in various production modes. The dominant contribution to the significance of the observed excess comes from the measurement of the VH , $H \rightarrow b\bar{b}$ cross section, performed with around 80 fb^{-1} of 13 TeV and 25 fb^{-1} of 7 and 8 TeV pp collisions.

The VH , $H \rightarrow b\bar{b}$ analysis performed by CMS is rather similar to the ATLAS one. Three channels, based on the number (0, 1, 2) of charged leptons (electrons or muons), are considered. For each channel, a signal region enriched in VH events is selected. Alternative selections lead to control regions enriched in events from individual background processes. The Higgs boson signal and background yields are determined from a simultaneous binned-likelihood fit to the

distributions of discriminating variables in the signal and background regions. All sources of systematic uncertainty are included in the fit as independent nuisance parameters. The analysis procedure is validated with a diboson cross section measurement.

Simulated signal and $t\bar{t}$ or single-top background samples are generated with the same event generators as ATLAS; V +jet events and diboson events (but also s -channel single top production) are generated with MADGRAPH5 AMC@NLO (interfaced to PYTHIA 8 for parton shower and hadronisation) instead of SHERPA or POWHEG. Diboson background events are generated with NLO matrix elements for real emission of up to two additional partons. V +jet events are generated with LO matrix elements for real emission of up to four additional partons.

Events are collected with missing transverse momentum (0-lepton channel), single-lepton (1-lepton) and di-lepton (2-lepton) triggers. The offline selection requires exactly 0, 1, or 2 charged leptons (muons or electrons) passing quality and isolation lepton requirements, and exactly two b -tagged jets with $|\eta| < 2.5$. The b -tagging requirements use different working points: a tighter one with misidentification rate of 0.1% for light quark and gluon jets and efficiency around 70% for b -jets, and a looser one with a 10% misidentification rate and an efficiency around 85%. The leptons are required to have $p_T > 25(30)$ GeV in the 1-lepton muon (electron) channel, and $p_T > 20$ GeV in the 2-lepton channel. In the two-lepton channel leptons are required to have same flavour, opposite sign, and invariant mass in the range 75–105 GeV. The two b -tagged jets are required to have p_T greater than (60, 35), (25, 25), and (20, 20) GeV in the 0-, 1-, and 2-lepton channels, respectively. The vector boson transverse momentum is required to be greater than 170 GeV in the 0-lepton channel (using the transverse momentum imbalance), 150 GeV in the 1-lepton channel (from the transverse momentum imbalance and the lepton transverse momentum vector), and 50 GeV in the 2-lepton channel. Two p_T^V categories (below or above 150 GeV) are defined in the latter. Background from $t\bar{t}$ in the 1-lepton channel is suppressed by vetoing events with two or more extra jets with $p_T > 30$ GeV and $|\eta| < 2.5$, and background from QCD multi-jet production is suppressed in the 0-lepton channel by requirements on the angular separation between the missing transverse momentum vector and its nearest jet.

The invariant mass resolution of the two jets selected to reconstruct the Higgs boson candidate is improved by recovering final-state radiation adding to the m_{jj} calculation the momenta of the jets near to either of the Higgs boson candidate jets. In the 2-lepton channel, similarly to what is done in the ATLAS analysis, transverse momentum conservation is exploited in a kinematic fit that requires that the p_T of the dilepton and dijet systems balance each other within the experimental uncertainty. The average resolution on m_{jj} is 10–13%.

The discriminating variable used in the final fit is the output of a deep neural network which uses as input several variables, among which the most discriminating ones are m_{jj} , p_T^V , the b -tagging score of the two jets, the number of additional jets in the event, and the angular separation between the two jets forming the Higgs boson candidate. The neural network training is performed separately for each channel, using simulated signal and background samples.

In the 2017 data an excess with respect to the background with an observed (expected) significance of 3.3 (3.1) standard deviations is found, corresponding to a signal strength $\mu = 1.08 \pm 0.26(\text{stat.})_{-0.20}^{+0.23}(\text{syst.})$. The breakdown of the uncertainties on μ is given in Table 7.6.

The diboson cross-check analysis leads to the observation of a significant excess with an observed (expected) significance of 5.2 (5.0) standard deviations, with a signal strength $\mu = 1.05 \pm 0.22$ in good agreement with the Standard Model.

The combination of these VH , $H \rightarrow b\bar{b}$ results with those of the same analysis performed on 35.9 fb^{-1} of 13 TeV data collected in 2015 and 2016 leads to an observed (expected) signal significance of 4.4 (4.2) standard deviations, with a signal strength $\mu = 1.06 \pm 0.26$. A further combination with previous results based on Run 1 data leads to an observed (expected) sig-

Table 7.6 – Breakdown of the contributions to the uncertainties in μ in the VH , $H \rightarrow b\bar{b}$ CMS measurement based on 44 fb^{-1} of 13 TeV pp collisions.

Source of uncertainty	σ_μ
Total	+0.35 −0.33
Statistical	± 0.12
Floating normalisations	± 0.035
Systematic	+0.23 −0.20
Experimental uncertainties	
Jet energy scale and resolution	± 0.05
Lepton identification	+0.02 −0.01
b-tagging	+0.09 −0.08
Luminosity	± 0.03
Other	+0.06 −0.05
Theoretical and modelling uncertainties	
Signal modeling	+0.07 −0.04
Background modeling	± 0.08
MC statistical	± 0.12

nal significance of 4.8 (4.9) standard deviations, with a signal strength $\mu = 1.01 \pm 0.22$. The results are very similar to those obtained by the ATLAS Collaboration. A combination with other CMS measurements of the $H \rightarrow b\bar{b}$ decay in the gluon fusion, vector boson fusion, and associated production with top quarks collected in Run 1 and/or Run 2 finally yields an observed (expected) signal significance of 5.6 (5.5) standard deviations, with a signal strength $\mu = 1.04 \pm 0.20$, providing an independent observation of this decay mode of the Higgs boson.

7.3 VH simplified template cross section measurements with $H \rightarrow b\bar{b}$ decays

A cross section measurement that is more granular and has smaller theoretical uncertainties compared to the inclusive signal strength or total cross section measurement presented in the previous sections can be performed by doing differential studies and using of a fiducial definition of the phase space in which the cross sections are measured. This is the goal of the simplified template cross section (STXS) framework, described in Section 7.3.1. Section 7.3.2 describes the measurement of simplified template VH cross sections with $H \rightarrow b\bar{b}$ decays using the same 80 fb^{-1} of 13 TeV pp collisions analysed for the observation of the $H \rightarrow b\bar{b}$ decay and the measurement of the inclusive signal strengths μ described in Section 7.1 and in Ref. [24]. The analysis is still being reviewed internally by the ATLAS Collaboration, but a publication of the results in the near future is foreseen. I am one of the three main contributors to these studies and editors of the ATLAS internal supporting document in which the details of the analysis are described.

7.3.1 The Simplified Template Cross Section framework

The concept of simplified template cross sections [29] was developed in the past few years to provide a way to perform measurements that

- are more granular than the signal strength measurements of Run 1;
- are less affected by theoretical uncertainties;
- can allow using advanced analysis techniques such as event categorization, multivariate techniques, and so on;
- can allow the combination of results from the analysis of different Higgs boson production modes.

To satisfy the first requirement, which has the goal of providing more information for theoretical interpretations, the phase space is divided in several mutually exclusive regions, in which the cross sections are measured.

The second requirement is satisfied by having such regions pass some fiducial criteria that reduce the theoretical uncertainties due to large extrapolations when going from the phase space selected by the analysis criteria to the phase space in which the cross sections are measured. An additional way in which the measurements are made more resilient against theoretical uncertainties is by changing the observable of interest from the ratio between observed and predicted

cross sections (*i.e.* signal strengths), in which uncertainties on the predicted Higgs boson cross sections and branching ratios enter in the denominator, to cross sections themselves. The cross section and branching ratio uncertainties are thus factorised and left to the theoretical predictions that enter later in the interpretation step. This makes the measurements more useful on the long-term as they are less affected by improvements in the theory calculations, which usually take time to be propagated properly to the experimental results, and makes it easier to compare the results against updated (or alternative, such as BSM) theory predictions.

The third requirement is met by using a simplified selection to define the fiducial volume, so that there is no attempt – unlike the case of “fully” fiducial differential cross section measurements – to make the particle-level selection as close as possible to the reconstruction-level one in order to minimise extrapolations and associated uncertainties. This way, one accepts to have slightly larger theoretical uncertainties than for fiducial cross section measurements, but reconstructed-level criteria can fully exploit event categorisations and advanced (e.g. multivariate) analysis techniques to improve signal-to-background discrimination.

In order to satisfy the fourth requirement of making it possible to combine all possible Higgs boson decay channels, the fiducial volumes are defined based only on the kinematic properties of the Higgs boson production (such for instance as the Higgs boson transverse momentum, or the number of jets produced in association with the Higgs boson), but not on the properties of the Higgs boson decay products, which differ from one final state to another.

Simplified template cross section measurements are complementary to “fully” fiducial and differential measurements but are not designed to replace these. Fully fiducial differential measurements, which are optimised for maximal theory independence, are still essential for a complete understanding of the Higgs boson production and decays, but they can only be performed relatively easily in a subset of decay channels, and do not discriminate between production modes, thus offering limited sensitivity to the different couplings of the Higgs boson to different particles.

The measured exclusive regions of phase space are specific to the different production modes. Their definitions are motivated by the previous requirements, with two extra goals of maximizing the experimental sensitivity while minimising the number of regions, and of isolating possible BSM effects in regions which are potentially more sensitive to them, like typically regions of high Higgs boson transverse momentum that could arise in high- p_T transfer events mediated by new massive particles. In practice, it is hard to define a set of regions that satisfies all of the previous requirements for every final state and production mode. Moreover, future addition of more data will make it possible to probe a larger number of smaller phase space regions. For this reason, three stages (0, 1, 2) with an increasing number of regions have been proposed.

So-called “stage-0” regions are simply cross sections splitted by production mode, as shown in Figure 7.7, in a fiducial Higgs boson pseudorapidity region $|y_H| < 2.5$ mainly driven by the ATLAS and CMS detector acceptance for most of the reconstructed particles (leptons, photons, b -jets). VBF and VH , $V \rightarrow qq$ processes, that lead to the same final state particles, are considered as part of the same “EW qqH” region. VH events with leptonic V boson decays are isolated in a separate region, which combines the three processes $q\bar{q} \rightarrow WH$, $q\bar{q} \rightarrow ZH$, and $gg \rightarrow ZH$. Recent measurements with 80 fb^{-1} of 13 TeV ATLAS data of stage-0 simplified template cross sections, with some merging due to lack of sensitivity of the current data to rarer decay modes like $b\bar{b}H$ (merged with ggF), tH (merged with $t\bar{t}H$) and individual VH production modes, have been obtained with $H \rightarrow \gamma\gamma$ decays [31] and $H \rightarrow ZZ^* \rightarrow 4\ell$ decays [35], with results in good agreement with SM predictions.

A finer granularity is provided by the “stage-1” STXS regions. They amount to 31 regions, splitted typically according to the number of jets produced in the event (excluding – if present

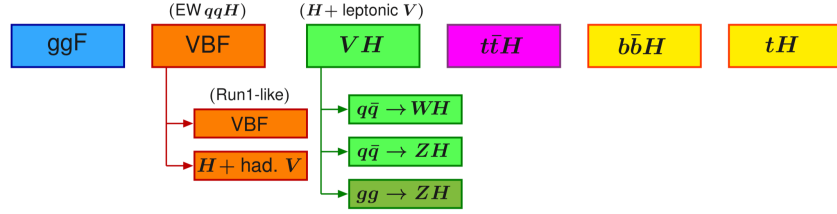


Figure 7.7 – Stage-0 simplified template cross section regions. A fiducial Higgs boson pseudorapidity requirement $|y_H| < 2.5$ is applied.

– jets from Higgs boson decay themselves) and the transverse momentum of the Higgs boson or of the vector boson V produced in association with the Higgs boson in the case of VH events. Refs. [31] and [35] also contain some “reduced” stage-1 STXS measurements of ggF and VBF regions, after merging together regions for which the data lacks sufficient sensitivity. For VH , $V \rightarrow \text{leptons}$, the stage-1 STXS regions are shown in Figure 7.8. First of all, the regions are separated according to the production mode. Inside production modes, further splitting is performed based on p_T^V , smaller or larger than 150 GeV. For qq -initiated processes, an extra high- p_T^V bin potentially more sensitive to BSM effects is defined as $p_T^V > 250$ GeV. The 150 – 250 GeV $qq \rightarrow VH$ regions and the > 150 GeV $gg \rightarrow ZH$ region are split according to the presence or not of extra jets in the event. The “(+)” symbol in the figure shows potential merging of regions for which data is insufficient to resolve them. Given the small VH production cross section, the only decay mode that currently provides sufficient sensitivity to resolve (at least some of) the stage-1 STXS VH region is the $H \rightarrow b\bar{b}$ one, with its large branching ratio of 58%. The measurement of these cross sections with 80 fb^{-1} of 13 TeV ATLAS data, using the sample of events selected in the analysis that led to the observation of $H \rightarrow b\bar{b}$ described at the beginning of this chapter, is detailed in the next section.

7.3.2 Simplified Template Cross Section measurements with VH , $H \rightarrow b\bar{b}$

The VH simplified template cross sections have been measured using 80 fb^{-1} of 13 TeV pp collisions collected by ATLAS in 2015–2017. Events are selected and classified in event categories in exactly the same way as in the analysis described in Section 7.1. A fit to the same observables is performed, but instead of a single signal shape (BDT_{VH} or m_{jj}) or yield per category, multiple shapes or yields are introduced, one for each STXS region under study.

The current data is not enough to constrain all the stage-1 VH simplified template cross sections, and some merging has thus been performed as described later. For technical reasons, to allow for some flexibility in the choice of the regions to be merged, to start from regions that are closer to the experimental categories, and also to make it possible to study the sensitivity to finer regions with more data to be collected in the future (study not presented in this manuscript), a finer splitting has been first considered. This splitting, called *maximum split* in the following, proceeds in this way:

- first, the VH (leptonic) signal is divided in five production and decay modes, $qq \rightarrow Z(\nu\nu)H$, $gg \rightarrow Z(\nu\nu)H$, $qq \rightarrow W(\ell\nu)H$, $qq \rightarrow Z(\ell\ell)H$, $gg \rightarrow Z(\ell\ell)H$;

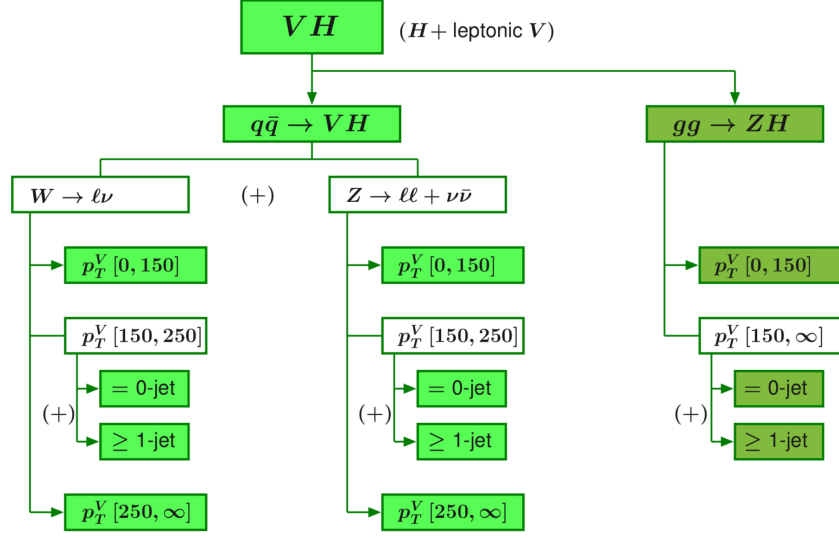


Figure 7.8 – Stage-1 simplified template cross section regions for associated production of a Higgs boson with weak gauge bosons decaying to leptonic final states. A fiducial Higgs boson pseudorapidity requirement $|y_H| < 2.5$ is applied.

- second, each mode is divided into a “forward Higgs” region and a “central Higgs” region according to the Higgs boson rapidity, whether $|y^H|$ is greater or smaller than 2.5, where this threshold basically matches the detector acceptance for signal jets from the Higgs boson decay (due to b -tagging) and for charged leptons;
- third, the central Higgs boson regions are further split according to the vector boson transverse momentum, p_T^V , in five smaller regions, corresponding to the intervals 0 – 75 GeV, 75 – 150 GeV, 150 – 250 GeV, 250 – 400 GeV, > 400 GeV;
- fourth, each of the p_T^V central Higgs boson regions are split according to the number of jets (0, 1, or at least 2) with $p_T > 30$ GeV produced in the event in association with the V and Higgs bosons.

The splitting is based on particle-level quantities. Jets are clustered from true stable particles using the anti- k_t algorithm with a radius parameter $R = 0.4$; particles from the Higgs boson decay are used. The maximum split has thus 80 regions. They are shown in Figure 7.9. For simplicity, the splitting of the $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production modes according to the Z boson decay mode ($\nu\nu$ or $\ell\ell$) are not shown. This latter merging effectively corresponds to the splitting scheme that in the following will be called “stage-1++”.

The expected cross sections for each region in the maximum splitting scheme are shown in Figure 7.10. They are obtained by computing, from simulated signal samples, the fractions of events in each region, and multiplying such fractions by the theoretical predictions of the inclusive cross sections (at NNLO in QCD and NLO in EW theory) compiled in Ref. [29].

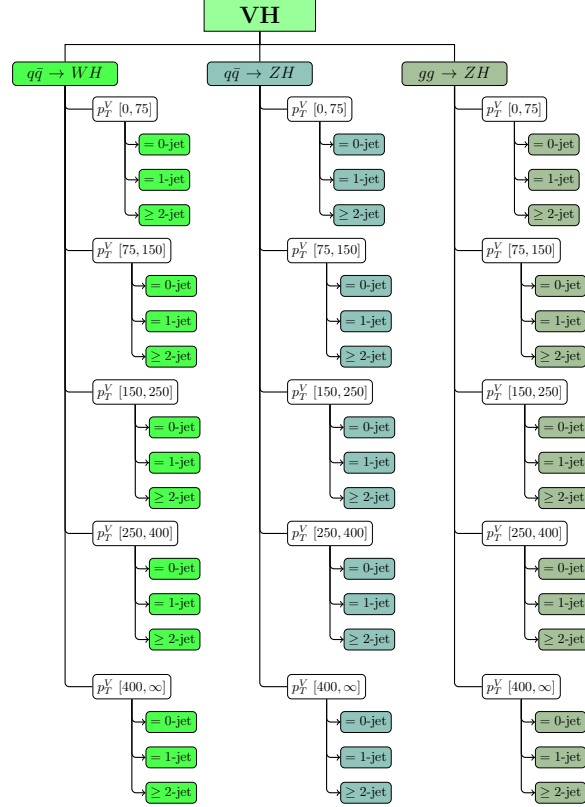


Figure 7.9 – VH simplified template cross section regions in the maximum splitting scheme. For simplicity, the forward Higgs boson regions and the splitting of the $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production modes according to the Z boson decay mode ($\nu\nu$ or $\ell\ell$) are not shown.

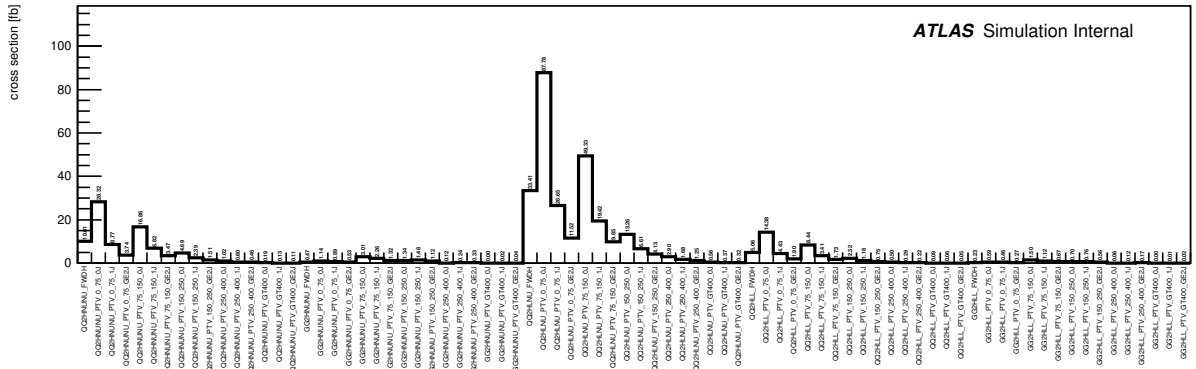


Figure 7.10 – SM cross section in each region of the maximum splitting scheme.

The expected cross sections for each region in the stage-1 splitting scheme are shown in Figure 7.11.

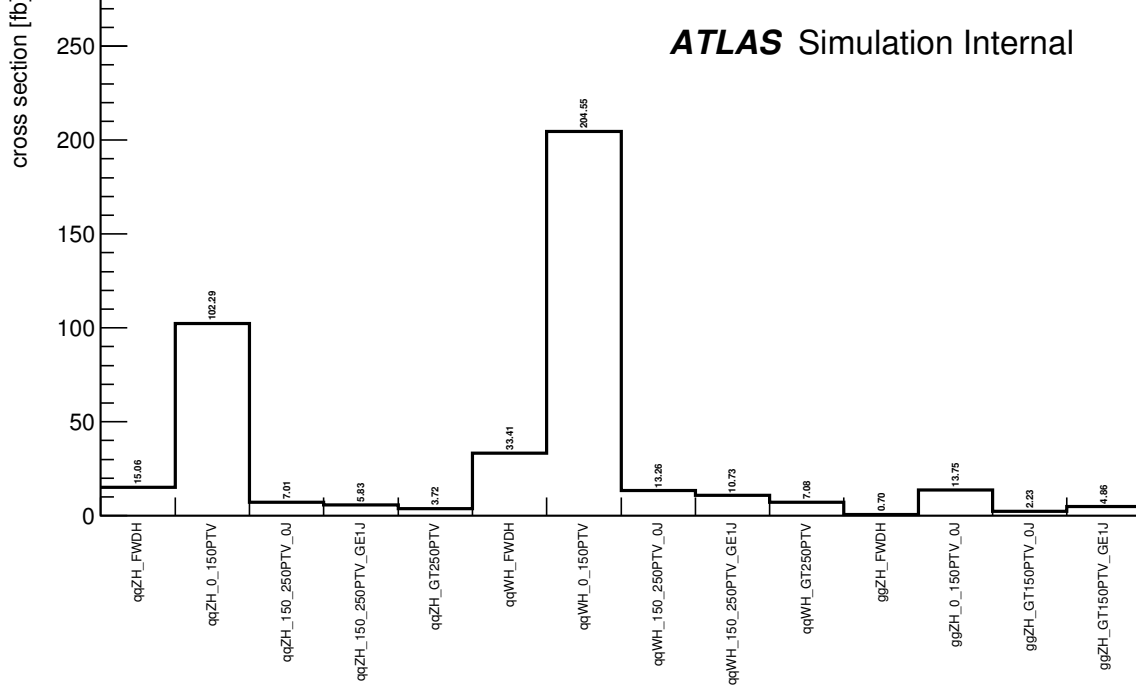


Figure 7.11 – SM cross section in each region of the stage-1 splitting scheme (Figure 7.8).

The measurement presented here uses a coarser splitting, which is even less granular than that of stage-1. The previous regions are merged together into six regions in the following way. The different ZH production and Z boson decay modes are all merged together. No splitting is applied based on the number of extra jets is applied. This splitting is shown in Figure 7.12.

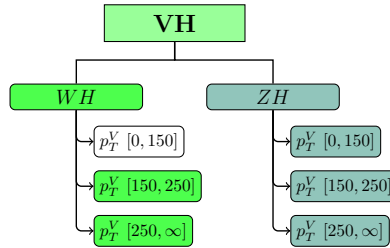


Figure 7.12 – VH simplified template cross-section regions used for the measurement presented in this thesis.

The expected cross-sections of each region in the splitting scheme adopted in this thesis are shown in Figure 7.13.

The event categories of the VH , $H \rightarrow b\bar{b}$ analysis are sensitive to these regions in the following way. 0- and 2-lepton categories are mostly sensitive to ZH while the 1-lepton events are mostly sensitive to WH production. The 2-lepton 75 – 150 GeV category provides sensitivity to the ZH $0 < p_T^V < 150$ GeV region, while the 0, 1 and 2-lepton > 150 GeV categories provide sensitivity to

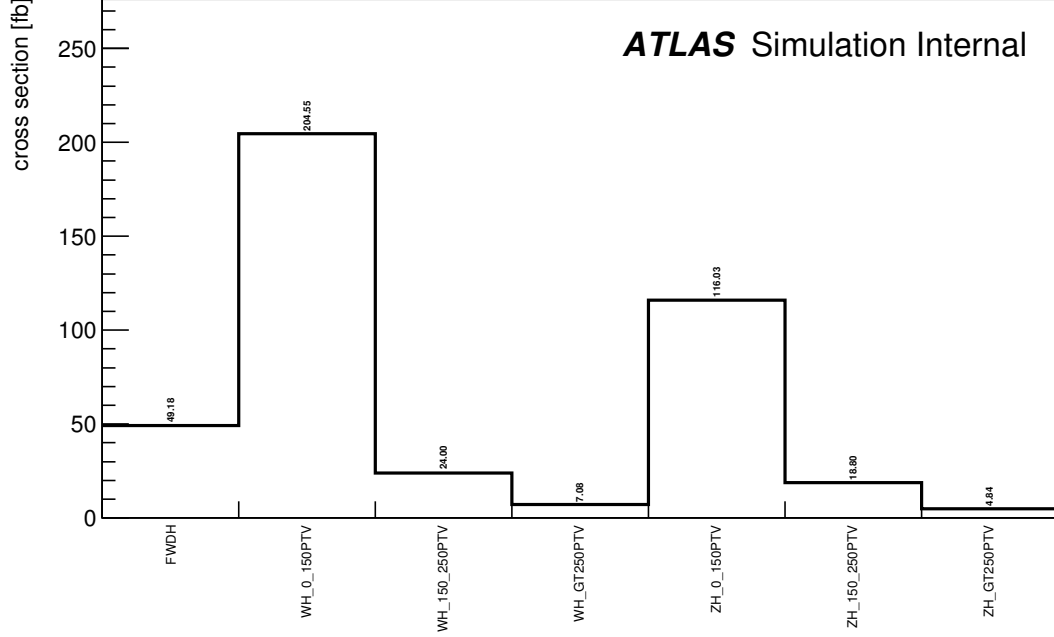


Figure 7.13 – SM cross section in each region of the splitting scheme used for the measurement presented in this thesis.

the ZH and WH $150 < p_T^V < 250$ GeV and $p_T^V > 250$ GeV regions (through their different BDT_{VH} shapes, as it will be shown later). The only region among these six to which the data with the current selection and categories do not provide enough sensitivity is the WH $0 < p_T^V < 150$ GeV region, due to the fact that the 1-lepton selection applies a $p_T^V > 150$ GeV requirement. In the future, sensitivity to this region could be recovered by introducing in the analysis a low- p_T^V (< 150 GeV) category. In the measurement presented here, the signal cross section in that region is set equal to the Standard Model prediction with a 50% relative uncertainty. Since this region is expected to contribute only marginally to the selected event sample, the impact on the results is minimal.

The expected event yield in each reconstructed category due to the different regions, the fraction of events in each reconstructed category originating from the different regions and the acceptance for each region and reconstructed category are shown in Figure 7.14 for the maximum-split scheme, in Figure 7.15 for the stage1-split scheme, and in Figure 7.16 for the splitting scheme used by the final measurement. The signal regions and the W +HF control region are shown, while the top $e\mu$ control regions are not shown since the signal contribution there is negligible.

Despite the reconstructed categories do not distinguish between events with p_T^V below or above 250 GeV, sensitivity to the two regions 150–250 GeV and > 250 GeV is provided by the different BDT_{VH} shape expected for events in the > 150 GeV reconstructed category that originate from either of the two regions. This is due mainly to the fact that one of the inputs to the BDT is indeed p_T^V . This is illustrated as an example in Figure 7.17 for the 0-lepton and 1-lepton channel and in Figure 7.18 for the 2-lepton channel.

An important part of this work on the STXS measurement is, in addition to the implementation of the likelihood model in order to fit the data and determine the cross sections, the

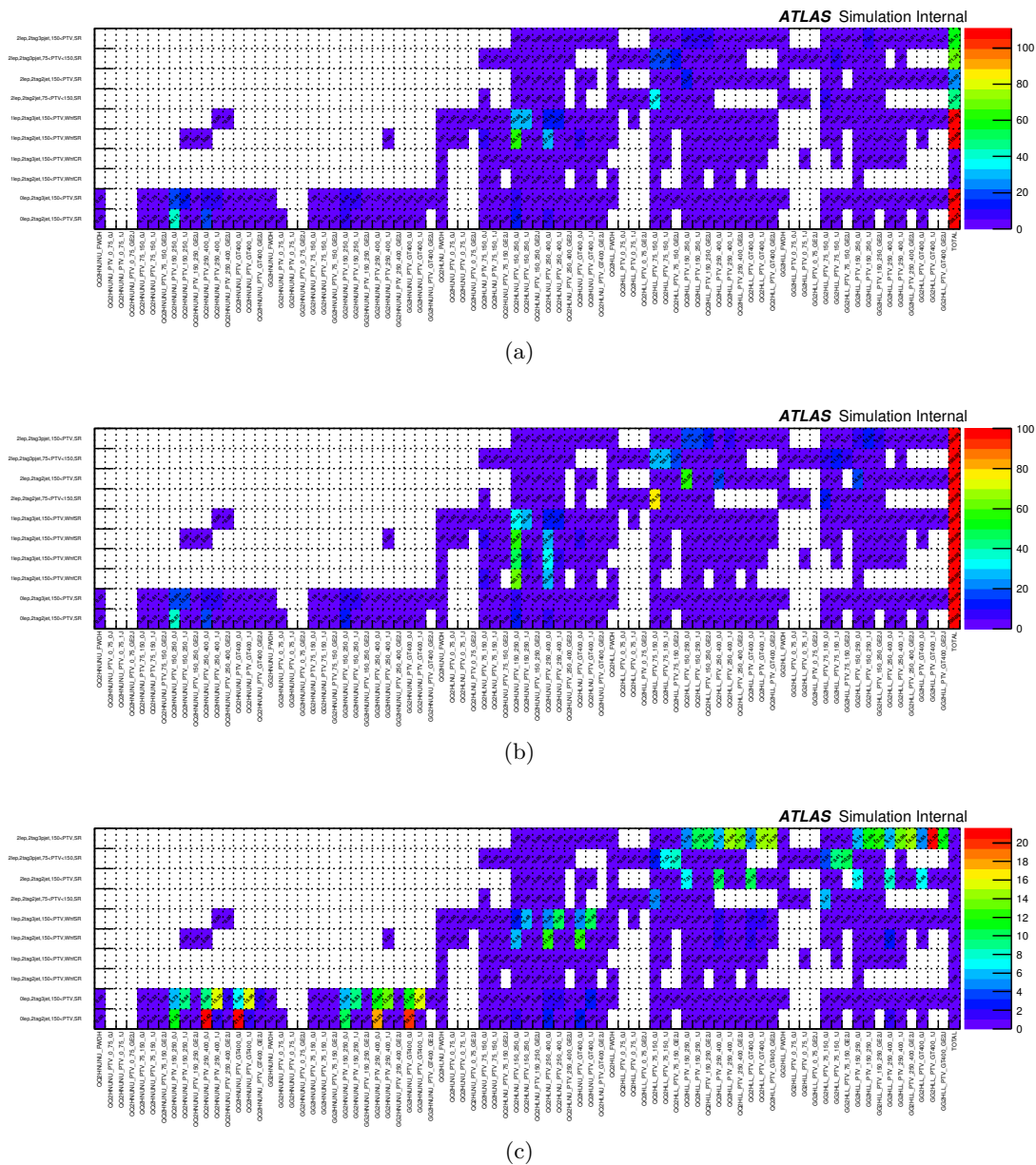


Figure 7.14 – In the maximum splitting scheme, (a) the expected yield of signal events in each reconstructed category, as a function of the STXS region; (b) the purity in percentage of each STXS bin in each reconstructed category (defined as the fraction of events reconstructed in one category that are due to a specific STXS region); (c) the acceptance (in percentage) of each STXS region in each reconstructed category (defined as the ratio between the expected yield shown in in (a) and the cross section shown in Figure 7.10). The STXS regions are shown along the x axis, while the reconstructed categories are shown along the y axis. The last columns show the sums over all regions for the same reconstructed category.

7.3 VH simplified template cross section measurements with $H \rightarrow b\bar{b}$ decays

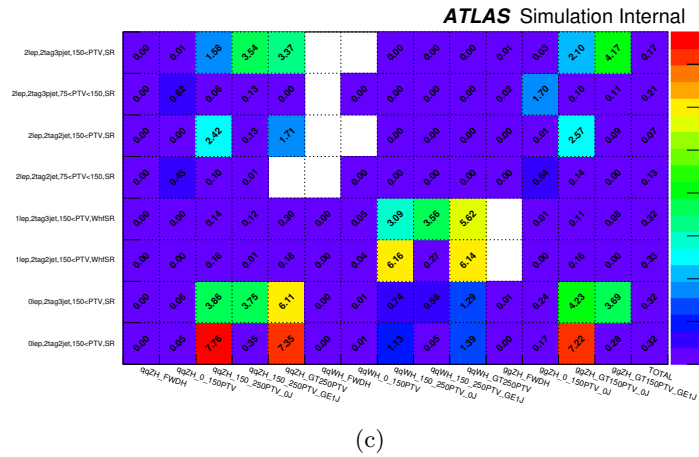
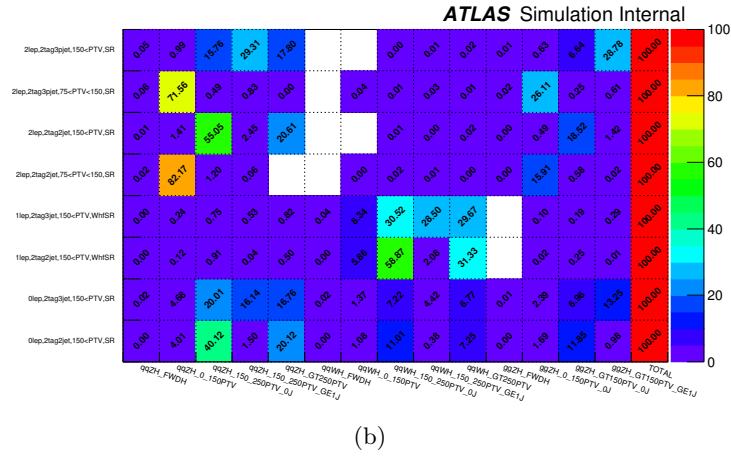
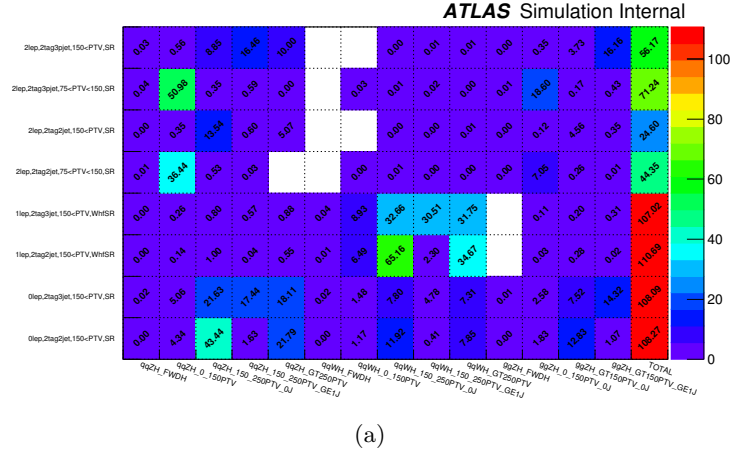
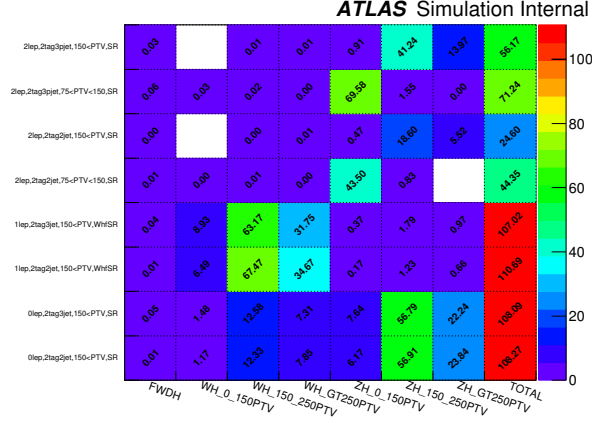
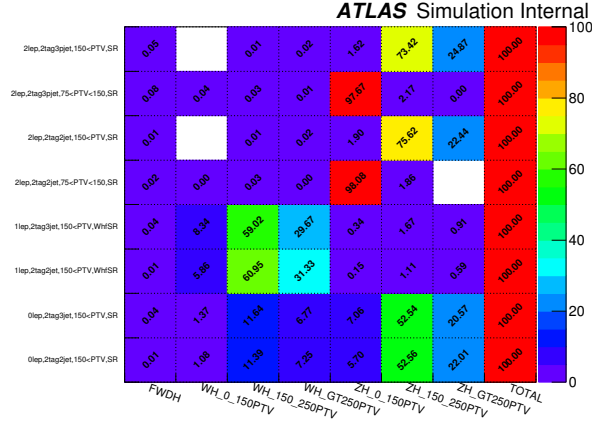


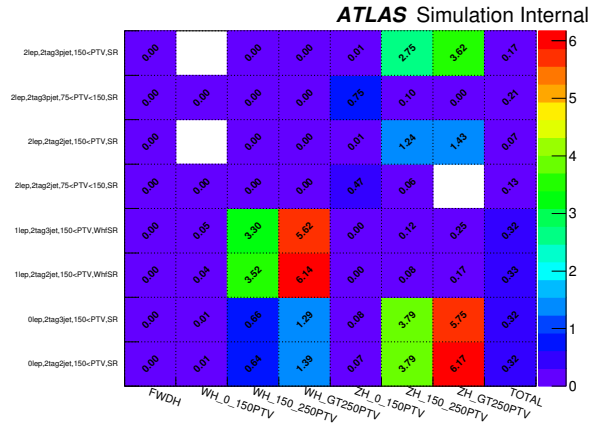
Figure 7.15 – In the stage-1 splitting scheme, (a) the expected yield of signal events in each reconstructed category, as a function of the STXS region; (b) the purity in percentage of each STXS bin in each reconstructed category; (c) the acceptance (in percentage) of each STXS region in each reconstructed category (defined as the ratio between the expected yield shown in in (a) and the cross section shown in Figure 7.11). The STXS regions are shown along the x axis, while the reconstructed categories are shown along the y axis. The last columns show the sums over all regions for the same reconstructed category.



(a)



(b)



(c)

Figure 7.16 – In the splitting scheme used in the measurement presented in this thesis, (a) the expected yield of signal events in each reconstructed category, as a function of the STXS region; (b) the purity in percentage of each STXS bin in each reconstructed category; (c) the acceptance (in percentage) of each STXS region in each reconstructed category (defined as the ratio between the expected yield shown in in (a) and the cross section shown in Figure 7.13). The STXS regions are shown along the x axis, while the reconstructed categories are shown along the y axis. The last columns show the sums over all regions for the same reconstructed category.

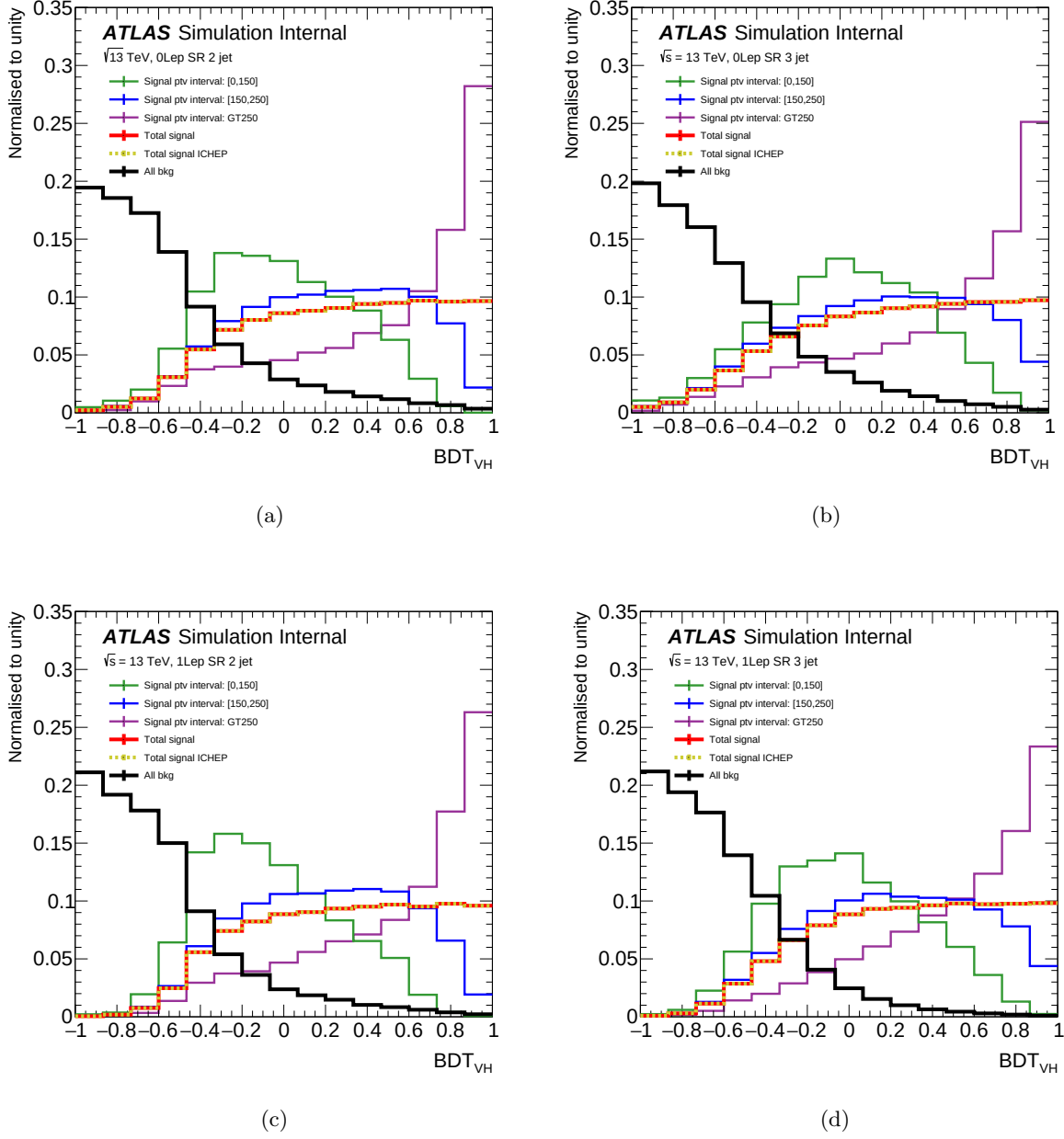


Figure 7.17 – BDT_{VH} distributions for different p_T^V STXS regions in the 0-lepton channel (a) 2-jet and (b) 3-jet, and 1 lepton channel (c) 2-jet signal and (d) 3-jet signal reconstructed categories. The distributions of the total signal and background are also shown. The BDT distributions have been scaled to the same area in order to highlight the shape differences. As a cross-check, the total signal shown with red lines, obtained from the sum of the shapes in the three STXS regions (with proper normalisations), is compared to the inclusive signal shape in yellow taken from the inclusive cross section measurement of Section 7.1.

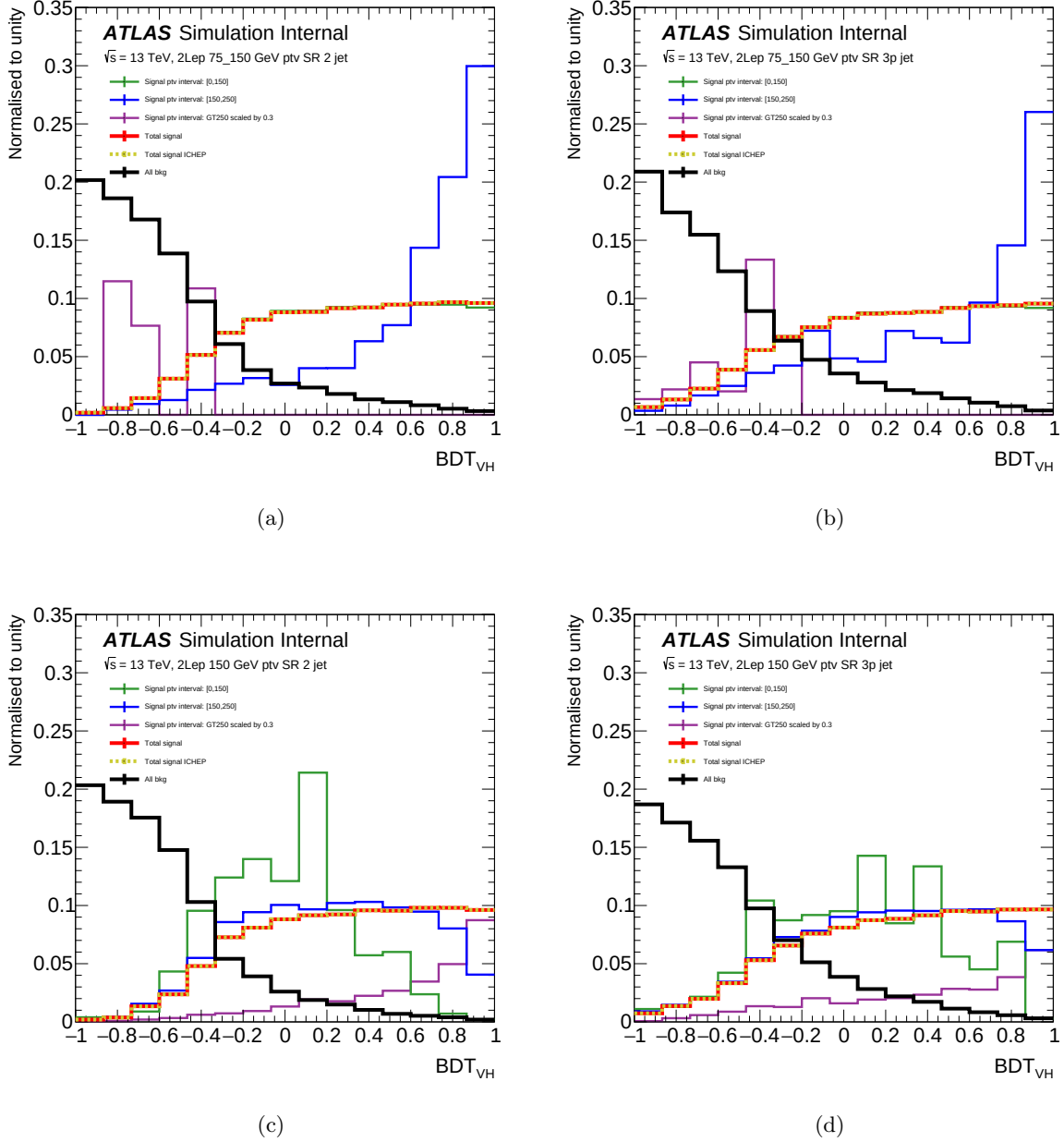


Figure 7.18 – BDT_{VH} distributions for different p_T^V STXS regions in the 2-lepton channel (a) 2-jet, $75 < p_T^V < 150$ GeV, (b) 3-jet $75 < p_T^V < 150$ GeV, (c) 2-jet, $p_T^V > 150$ GeV, (d) 3-jet $p_T^V > 150$ GeV reconstructed categories. The distributions of the total signal and background are also shown. The BDT distributions have been scaled to the same area in order to highlight the shape differences. As a cross-check, the total signal shown with red lines, obtained from the sum of the shapes in the three STXS regions (with proper normalisations), is compared to the inclusive signal shape in yellow taken from the inclusive cross section measurement of Section 7.1.

estimation of the uncertainties on the signal model, which arise from the further splitting of the phase space in the fiducial regions in which the measurement is performed. This is described to some extent in the following. Uncertainties have been calculated for each region of the stage-1++ splitting scheme, and then translated into uncertainties on the stage-1 regions by taking the weighted averages of the uncertainties in the stage-1++ regions, with weights proportional to the cross section of each region.

7.3.2.1 QCD scale uncertainties

QCD scale uncertainties account for the impact of higher order terms in the perturbative expansion of the cross section that have been neglected. Such uncertainties are computed by varying the renormalisation scale μ_R and the factorisation scale μ_F independently in a range between 0.5 and 2 times their nominal value (equal to 1 in units of some characteristic kinematic quantity of the hard-scattering process). The six scale variations considered are:

$$[\mu_R, \mu_F] : [0.5, 1][1, 0.5][2, 1][1, 2][0.5, 0.5][2, 2]$$

The calculation of these uncertainties has been determined following the recommendations of Refs. [123, 29]. For simplicity I illustrate first the case of a two-region splitting. Let us consider a single boundary a/b that splits the phase space in two regions a and b . The splitting can either be based on the vector boson p_T^V or the number of extra jets, n_{jet} . The cross sections in the two regions defined by the splitting are σ_a and σ_b , and they are related to the total cross section σ_{ab} by $\sigma_{ab} = \sigma_a + \sigma_b$. Let us denote the absolute uncertainty on the expected value of the total uncertainty σ_{ab} as Δ_{ab}^y . The total uncertainties on σ_a and σ_b are both the sum of two contributions:

- Δ_a^y and Δ_b^y : uncertainties on σ_a and σ_b due to the absolute uncertainty on the total cross section Δ_{ab}^y : $\Delta_{ab}^y = \Delta_a^y + \Delta_b^y$;
- $\Delta_{a/b}$: uncertainties on σ_a and σ_b due to the uncertainty on the fraction of events which belong to either of the two regions of phase space. This migration uncertainty affects the two regions in an anti-correlated way and should cancel when the regions are merged.

These uncertainties are implemented in the “workspace” containing the fit model as two independent nuisance parameters (NP), a *correlated NP* θ^y affecting simultaneously and in the same way all cross sections, and an *anti-correlated NP* $\theta_{a/b}$ that affect the cross sections in opposite ways. On the set of three quantities $\sigma_{ab}, \sigma_a, \sigma_b$ they act in the following way:

$$\theta^y : \{ \Delta_{ab}^y, \Delta_a^y, \Delta_b^y \} \quad (7.9)$$

$$\theta_{a/b} : \{ 0, \Delta_{a/b}, -\Delta_{a/b} \} \quad (7.10)$$

We consider now the general case of multiple regions. Each region can have more than one boundary, and each boundary can be shared by different regions. This case is treated by repeating the procedure described previously for any given single bin boundary a/b , with all additional subdivisions removed. Then, given the bin boundary a/b , additional binning cuts that further subdivide σ_a and σ_b as $\sigma_a = \sum_i \sigma_{ai}$ and $\sigma_b = \sum_j \sigma_{bj}$ can be included. Since the a/b boundary is interpreted as a common uncertainty source, it is considered as fully correlated among each set of sub-regions and implemented via a single nuisance parameter $\theta_{a/b}$, leading to uncertainties given by:

$$\theta_{a/b} : \Delta_{a/b} \times \{ \{x_{ai}\}, \{-x_{bj}\} \} \text{ with } \sum_i x_{ai} = \sum_j x_{bj} = 1$$

where the parameters x_{ai} and x_{bj} specify how the absolute uncertainty $\Delta_{a/b}$ gets distributed among the sub-regions. As an example, we consider the case in which we start from the full phase

space and then introduce a p_T^V split at 150 GeV. The migration uncertainty induced by such p_T^V cut will be fully anti-correlated between the regions $0 < p_T^V < 150$ GeV and $p_T^V > 150$ GeV. If the high p_T^V region is further split by a 250 GeV cut in two regions $150 < p_T^V < 250$ GeV and $p_T^V > 250$ GeV, the migration uncertainty induced by the cut at 150 GeV will be fully correlated among these two regions.

The procedure to estimate the migration uncertainties due to p_T^V and n_{jet} boundaries is described in the next paragraphs. One common feature is that the uncertainties have been computed in inclusive regions ($p_T^V \geq x$, $n_{\text{jet}} \geq x$) and then propagated to the final regions under study, since scale variations applied directly to exclusive fixed-order cross section predictions have been found to underestimate the perturbative uncertainty for such cross sections sections [118].

To compute the uncertainties due to the p_T^V splitting, the cross section variations induced by the six QCD scale variations are evaluated in four (semi) inclusive p_T^V regions: $p_T^V > 75$ GeV, $p_T^V > 150$ GeV, $p_T^V > 250$ GeV and $p_T^V > 400$ GeV. They are evaluated separately for the three production WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$. They are estimated from the generated POWHEG NLO VH signal samples. All the relative variations are smaller than 4% and the maximum relative variation is approximately constant across the inclusive p_T^V regions. We denote the maximum of the six scale variations in each region $p_T^V > x$ GeV $\delta_{[x,\infty]}$. In addition, the scale uncertainty on the overall cross section, denoted δ_{overall} , is taken from the NNLO calculations of Ref. [29]: it amounts to $\pm 0.7\%$ for WH , $\pm 0.6\%$ for $qq \rightarrow ZH$ and $\pm 25\%$ for $gg \rightarrow ZH$, where asymmetric uncertainties have been symmetrised by taking the largest of the absolute values of the positive or negative uncertainty. The final QCD scale relative uncertainties δ for the inclusive p_T^V regions for the WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production modes are shown in Figure 7.19. The overall cross section uncertainties are also shown in the same plots, in the first bin of each histogram. For WH and $qq \rightarrow ZH$ the overall uncertainty is significantly smaller than the uncertainties on the inclusive p_T^V regions.

The QCD scale uncertainties in each STXS region are then computed from the uncertainties in the inclusive p_T^V regions in the following way. Absolute uncertainties are computed as

$$\Delta^y = y_{\text{tot}} \times \delta_{\text{overall}} \quad (7.11)$$

$$\Delta_{75} = y_{[75,\infty]} \times \delta_{[75,\infty]} \quad (7.12)$$

$$\Delta_{150} = y_{[150,\infty]} \times \delta_{[150,\infty]} \times K \quad (7.13)$$

$$\Delta_{250} = y_{[250,\infty]} \times \delta_{[250,\infty]} \times K \quad (7.14)$$

$$\Delta_{400} = y_{[400,\infty]} \times \delta_{[400,\infty]} \times K \quad (7.15)$$

$$(7.16)$$

where y are the cross sections in each inclusive p_T^V region and K is a factor, equal to 0.5, chosen so that there is a reasonable closure when propagating back the scale uncertainties on the STXS regions to the inclusive p_T^V regions, with respect to the uncertainties on the inclusive regions computed before. Each Δ_x represents the migration uncertainty due to the splitting at $p_T^V = x$ GeV and is implemented in the workspace as fully anti-correlated between regions with $p_T^V > x$ GeV and $p_T^V < x$ GeV. This anti-correlation is introduced in the workspace through correlated nuisance parameters, with positive sign for $p_T^V > x$ GeV and negative sign for $p_T^V < x$ GeV. For example the impact of Δ_{250} is:

$$\begin{aligned} & -\Delta_{250}/y_{[0,250]} \text{ for STXS bins with } p_T^V < 250 \text{ GeV} \\ & \Delta_{250}/y_{[250,\infty]} \text{ for STXS bins with } p_T^V > 250 \text{ GeV} \end{aligned}$$

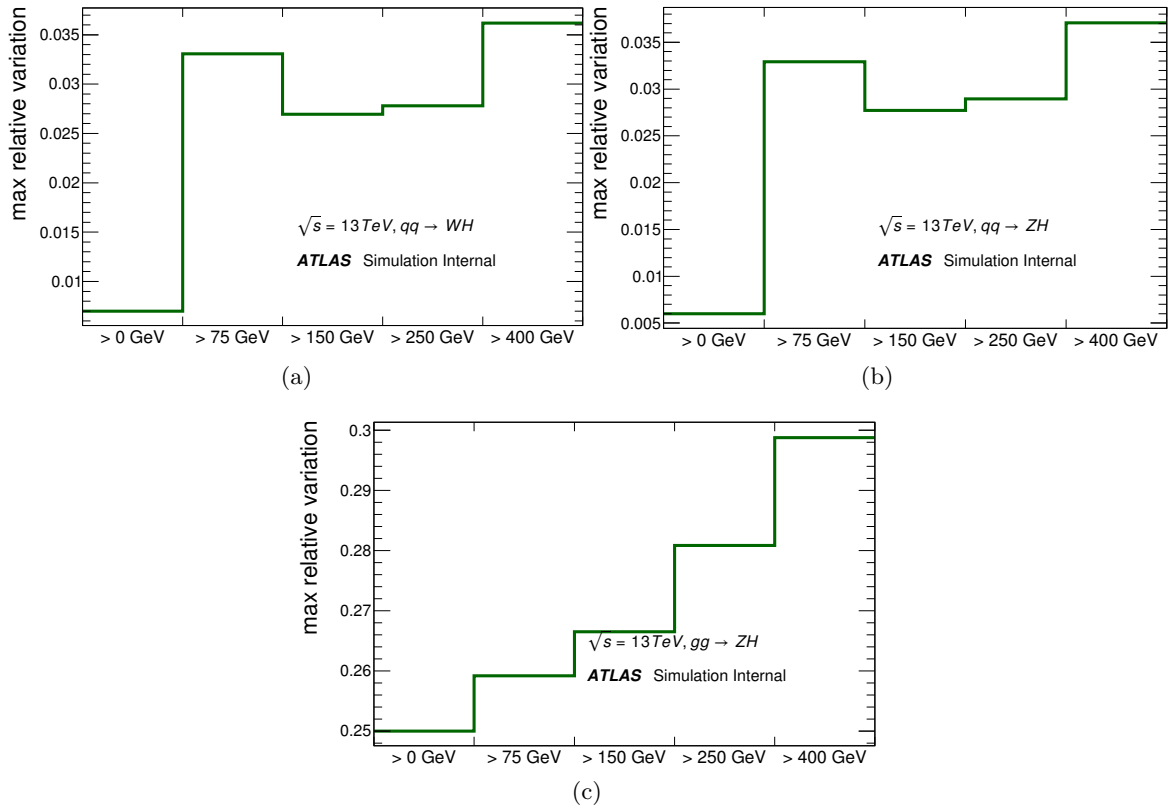


Figure 7.19 – Maximum of the six relative QCD scale variations computed in inclusive p_T^V regions, for the three production modes (a) WH , (b) $qq \rightarrow ZH$ (b), and (c) $gg \rightarrow ZH$. The overall scale uncertainties ($p_T^V > 0$ GeV), shown in the first bin of each histogram, are taken from the more accurate NNLO (in QCD) calculations of Ref. [29], while the others are computed from NLO simulations.

where $y_{[0,250]}$ and $y_{[250,\infty]}$ are the cross sections for the bins $p_T^V < 250$ GeV and $p_T^V > 250$ GeV respectively. The relative QCD scale uncertainties on the STXS stage-1++ regions for the WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production modes, as well as their sum in quadrature, are shown in Figure 7.20. The QCD scale uncertainties on the stage-1 simplified template cross sections are

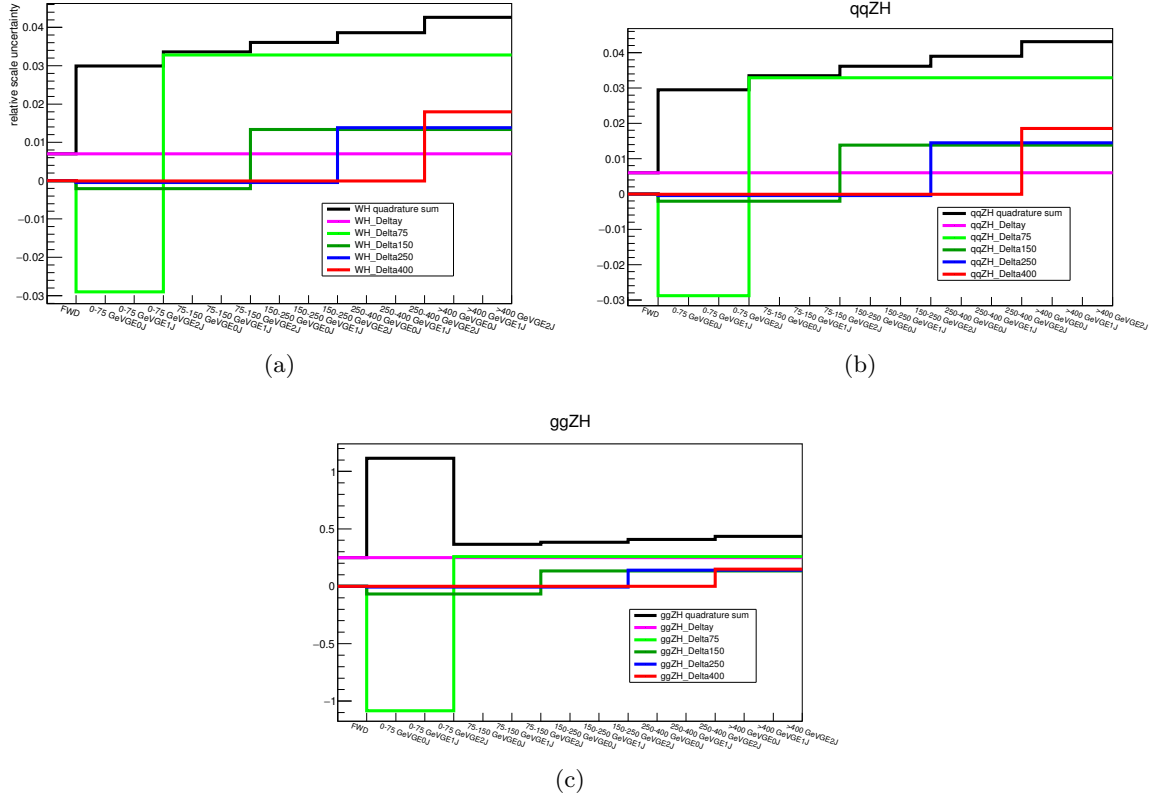


Figure 7.20 – Relative QCD scale uncertainties for the stage-1++ simplified template cross sections due to the p_T^V splitting and overall uncertainty for (a) WH , (b) $qq \rightarrow ZH$, and (c) $gg \rightarrow ZH$ (c). Δ_{75} , Δ_{150} , Δ_{250} and Δ_{400} are the four migration uncertainties due to the split in p_T^V , while Δ^y is the overall scale uncertainty on the cross section. The black line represents the sum in quadrature of all the scale uncertainties. The correction factor $K = 0.5$ is applied to Δ_{150} , Δ_{250} and Δ_{400} .

computed as weighted averages of the variations in stage1++ bins:

$$\text{Var}_{[250,\infty]} = \frac{\text{Var}_{[250,400]} \times y_{[250,400]} + \text{Var}_{[400,\infty]} \times y_{[400,\infty]}}{y_{[250,\infty]}}$$

where y are the cross sections in the various regions. They are summarised in Table 7.7. Uncertainties smaller than 0.5% are not shown in the Table and neglected in the fit.

QCD scale uncertainties due to migrations between n_{jet} regions are also shown in the same table and have been estimated similarly to p_T^V uncertainties, using the inclusive n_{jet} bins $n_{\text{jet}} \geq 1$ and $n_{\text{jet}} \geq 2$. They have been computed independently in each p_T^V exclusive region, for the stage-1++ splitting, and then merged to obtain the stage-1 cross section uncertainties of Table 7.7.

Table 7.7 – QCD scale uncertainties for the stage-1 binning. Var^y are uncertainties due to the knowledge of the overall cross section. Var_{75} , Var_{150} , Var_{250} and Var_{400} are migration uncertainties due to the p_T^V splitting. Var^1 and Var^2 are migration uncertainties due to the n_{jet} splitting. Uncertainties smaller than 0.5% are not shown.

	Var^y	Var_{75}	Var_{150}	Var_{250}	Var_{400}	Var^1	Var^2
$WH, p_T^V \in [0, 150] \text{ GeV}$	0.7	-0.52	-	-	-	-	-
$WH, p_T^V \in [150, 250] \text{ GeV}, 0\text{-jet}$	0.7	3.3	1.3	-	-	-4.1	-1.7
$WH, p_T^V \in [150, 250] \text{ GeV}, \geq 1\text{-jet}$	0.7	3.3	1.3	-	-	5	2
$WH, p_T^V \in [250, \infty] \text{ GeV}$	0.7	3.3	1.3	1.4	-	-	-
$gg \rightarrow ZH, p_T^V \in [0, 150] \text{ GeV}$	25	-14	-6.7	-0.79	-	-	-
$gg \rightarrow ZH, p_T^V \in [150, \infty] \text{ GeV}, 0\text{-jet}$	25	26	13	-	-	-58	-11
$gg \rightarrow ZH, p_T^V \in [150, \infty] \text{ GeV}, \geq 1\text{-jet}$	25	26	13	2.1	-	26	5.4
$qq \rightarrow ZH, p_T^V \in [0, 150] \text{ GeV}$	0.6	-	-	-	-	-	-
$qq \rightarrow ZH, p_T^V \in [150, 250] \text{ GeV}, 0\text{-jet}$	0.6	3.3	1.4	-	-	-4.6	-1.9
$qq \rightarrow ZH, p_T^V \in [150, 250] \text{ GeV}, \geq 1\text{-jet}$	0.6	3.3	1.4	-	-	5.5	2.4
$qq \rightarrow ZH, p_T^V \in [250, \infty] \text{ GeV}$	0.6	3.3	1.4	1.4	-	-	-

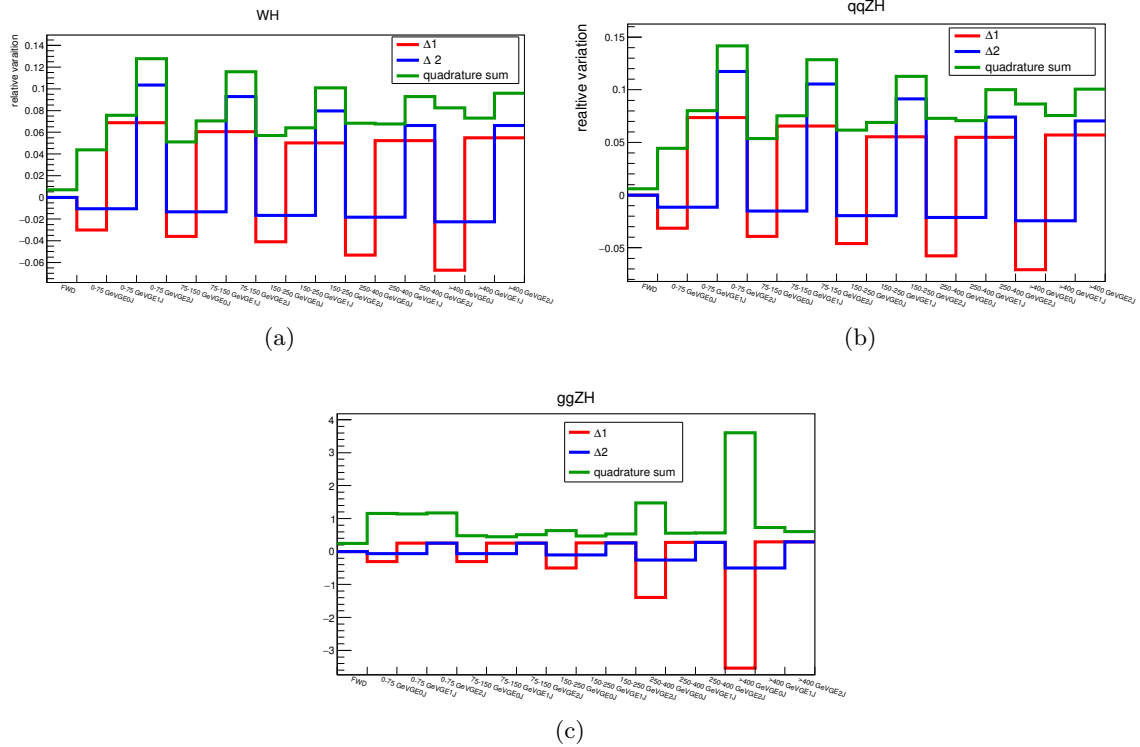


Figure 7.21 – Relative QCD scale uncertainties for the stage-1++ simplified template cross sections due to the n_{jet} splitting for (a) WH , (b) $qq \rightarrow ZH$, and (c) $gg \rightarrow ZH$. Δ_1 and Δ_2 are the uncertainties due to the $n_{\text{jet}} \geq 1$ and ≥ 2 splitting. The green line is the quadrature sum of all the uncertainties in a STXS bin: the overall uncertainties, the p_T^V migration uncertainties and the n_{jet} uncertainties.

The n_{jet} migration uncertainties are null for STXS regions that are inclusive in n_{jet} , such as the $p_T^V > 250$ GeV regions, while they are the largest source of QCD uncertainties (except for $gg \rightarrow ZH$) for the other regions.

7.3.2.2 PDF and α_s uncertainties

PDF and α_s uncertainties have been computed using the variations of the PDF4LHC15_30_as set [106]. This PDF set includes a nominal set of PDFs and 30 PDF variations that correspond to the same nominal value of $\alpha_s(m_Z^2) = 0.118$; in addition, it contains two PDF sets obtained for two alternative values of $\alpha_s(m_Z^2)$, $\alpha_s(m_Z^2) = 0.1165$ and $\alpha_s(m_Z^2) = 0.1195$.

The relative uncertainties in the STXS cross sections due to PDF uncertainties were computed in each STXS region as:

$$\text{Var}_i = \frac{y_{\text{PDF}i} - y_{\text{PDF0}}}{y_{\text{PDF0}}}$$

where y_{PDF0} and $y_{\text{PDF}i}$ are the cross sections in a STXS region for the nominal PDF (PDF0) and for an alternative PDF (PDF*i*).

The relative uncertainties in the STXS cross sections due to the α_s uncertainty were computed as the average:

$$\text{Var}_{\alpha_s} = \frac{|\text{Var}_{\alpha_s=0.1165}| + |\text{Var}_{\alpha_s=0.1195}|}{2}.$$

of the relative variations $\text{Var}_{\alpha_s=0.1165}$ and $\text{Var}_{\alpha_s=0.1195}$ of the $\alpha_s(m_Z^2) = 0.1165$ and $\alpha_s(m_Z^2) = 0.1195$ samples with respect to the nominal sample produced with $\alpha_s(m_Z^2) = 0.118$.

The PDF and α_s relative uncertainties computed for the stage-1++ STXS regions are shown in Figure 7.22. Most of the PDF variations lead to negligible uncertainties, lower than 0.5%. The α_s variation is represented with a dotted line and is amongst the largest variations. The uncertainties implemented in the final fit are those for the stage-1 STXS regions, shown in Table 7.8. Negligible variations, smaller than 0.5%, are not shown and are not implemented in the workspace.

7.3.2.3 Parton shower and underlying event model uncertainties

Uncertainties from the parton shower and underlying event model are determined by comparing signal samples produced with the nominal parton shower and underlying event model of PYTHIA 8 to those produced with an alternative model provided by HERWIG 7. Such uncertainties are still being quantified.

Table 7.8 – PDF and α_s relative cross section uncertainties for the stage-1 STXS regions. Each column corresponds to a different PDF or α_s variation. Since variations smaller than 0.5% are not shown, the columns corresponding to PDF variations that have an impact smaller than 0.5% on all stage-1 regions are not shown.

	PDF1	PDF2	PDF3	PDF4	PDF5	PDF6	PDF8	PDF9	PDF11	PDF12	PDF14	PDF17	PDF18	PDF19	PDF20	PDF22	PDF24	PDF28	α_s
$WH, p_T^V \in [0, 150]$ GeV	-	-	-	0.98	-	-	-	-	-	-	-0.75	-	-	-	0.72	-	-	-	1.2
$WH, p_T^V \in [150, 250]$ GeV, 0-jet	-	-0.71	-	1.1	-	0.71	-	-	-	-	-0.84	-	-	-	1.1	-	-	-	0.72
$WH, p_T^V \in [150, 250]$ GeV, ≥ 1 -jet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.61	-	-	-	1.3
$WH, p_T^V \in [250, \infty]$ GeV	0.8	-0.76	-	0.56	-	0.84	-	-	-	-	-	-	-	-	1	-	-	-	0.96
$gg \rightarrow ZH, p_T^V \in [0, 150]$ GeV	-	-0.83	-	-1.1	0.58	-0.69	-	-	-0.64	-	-	0.57	-	-0.77	-	-	-	0.9	1.2
$gg \rightarrow ZH, p_T^V \in [150, \infty]$ GeV, 0-jet	-	-1	-	-1.3	-	-0.86	-	-0.56	-0.78	-	-	0.8	-	-0.93	-	0.63	-	0.97	1.2
$gg \rightarrow ZH, p_T^V \in [150, \infty]$ GeV, ≥ 1 -jet	-	-0.98	-	-1.3	-	-0.82	-	-0.55	-0.75	-	-	0.77	-	-0.9	-	0.56	-	0.98	1.2
$qq \rightarrow ZH, p_T^V \in [0, 150]$ GeV	-	-	-	0.94	-	-	-	-	-	-	-0.63	-	-	-	0.68	-	-	-	1.2
$qq \rightarrow ZH, p_T^V \in [150, 250]$ GeV, 0-jet	-	-	-	1.2	-	0.7	-	-	-	-	-0.71	-	-	-	1	-	-	-	0.72
$qq \rightarrow ZH, p_T^V \in [150, 250]$ GeV, ≥ 1 -jet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.56	-	-	-	1.3
$qq \rightarrow ZH, p_T^V \in [250, \infty]$ GeV	0.81	-0.51	-	0.57	-	0.84	-	-	-	-	-	-	-	-	0.91	-	-	-	0.99

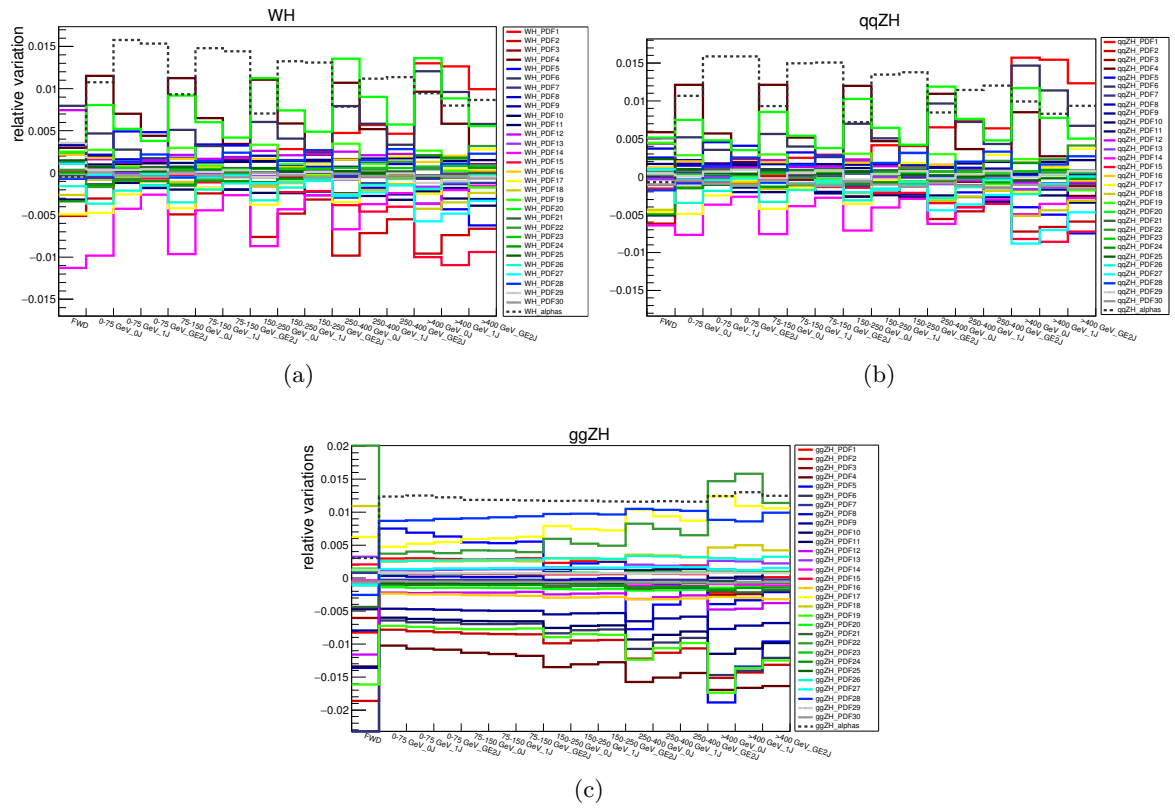


Figure 7.22 – PDF and α_s relative variations in STXS bins for (a) WH , (b) $qq \rightarrow ZH$, and (c) $gg \rightarrow ZH$. The α_s variation is represented with a dotted line.

7.3.2.4 Results

The measured simplified template cross sections for the five regions under study (the sixth one is constrained to the SM prediction as already mentioned) are shown in Figure 7.23. This is the first attempt to measure VH simplified template cross sections behind the inclusive stage-0 approach. The results are in good agreement with SM predictions. Uncertainties, both statistical and systematic ones, are fairly large; however, the POIs of this fit are “signal-strength-like” quantities, in which the simplified template cross sections have been divided by their SM prediction, and the uncertainty on the SM prediction itself has been folded into the measurement. This will be fixed in the future.

The contribution to the total uncertainty on each POI from each group of correlated uncertainties is summarised in Table 7.9.

Table 7.9 – Breakdown of the uncertainty on each of the five parameters of interest in the STXS fit.

POI $\mu_{WH}(150-250)$	Central Value 0.849505		POI $\mu_{WH}(\geq 250)$	Central Value 1.25171	
Set of nuisance parameters	Impact on error		Set of nuisance parameters	Impact on error	
Total	+1.054 / -1.038	± 1.046	Total	+0.774 / -0.716	± 0.745
DataStat	+0.682 / -0.678	± 0.680	DataStat	+0.647 / -0.608	± 0.627
FullSyst	+0.803 / -0.785	± 0.794	FullSyst	+0.425 / -0.379	± 0.402
Floating normalizations	+0.150 / -0.161	± 0.156	Floating normalizations	+0.124 / -0.100	± 0.112
Multi Jet	+0.047 / -0.049	± 0.048	Multi Jet	+0.014 / -0.015	± 0.014
Modelling: single top	+0.216 / -0.215	± 0.216	Modelling: single top	+0.081 / -0.078	± 0.079
Modelling: ttbar	+0.119 / -0.125	± 0.122	Modelling: ttbar	+0.094 / -0.085	± 0.089
Modelling: W+jets	+0.177 / -0.181	± 0.179	Modelling: W+jets	+0.189 / -0.198	± 0.194
Modelling: Z+jets	+0.101 / -0.111	± 0.106	Modelling: Z+jets	+0.036 / -0.023	± 0.030
Modelling: Diboson	+0.168 / -0.174	± 0.171	Modelling: Diboson	+0.046 / -0.043	± 0.045
Modelling: VH	+0.175 / -0.018	± 0.096	Modelling: VH	+0.182 / -0.055	± 0.118
Detector: lepton	+0.015 / -0.017	± 0.016	Detector: lepton	+0.011 / -0.008	± 0.009
Detector: MET	+0.023 / -0.027	± 0.025	Detector: MET	+0.016 / -0.010	± 0.013
Detector: JET	+0.148 / -0.078	± 0.113	Detector: JET	+0.064 / -0.031	± 0.047
Detector: FTAG (b-jet)	+0.108 / -0.138	± 0.123	Detector: FTAG (b-jet)	+0.131 / -0.073	± 0.102
Detector: FTAG (c-jet)	+0.253 / -0.231	± 0.242	Detector: FTAG (c-jet)	+0.029 / -0.029	± 0.029
Detector: FTAG (l-jet)	+0.120 / -0.119	± 0.120	Detector: FTAG (l-jet)	+0.024 / -0.023	± 0.024
Detector: FTAG (extrap)	+0.020 / -0.020	± 0.020	Detector: FTAG (extrap)	+0.024 / -0.024	± 0.024
Detector: PU	+0.001 / -0.027	± 0.014	Detector: PU	+0.021 / -0.005	± 0.013
Lumi	+0.039 / -0.004	± 0.022	Lumi	+0.034 / -0.006	± 0.020
MC stat	+0.403 / -0.420	± 0.411	MC stat	+0.268 / -0.282	± 0.275

POI $\mu_{ZH}(0-150)$	Central Value 1.5922		POI $\mu_{ZH}(150-250)$	Central Value 0.729573		POI $\mu_{ZH}(\geq 250)$	Central Value 1.74343	
Set of nuisance parameters	Impact on error		Set of nuisance parameters	Impact on error		Set of nuisance parameters	Impact on error	
Total	+1.150 / -0.903	± 1.027	Total	+0.698 / -0.662	± 0.680	Total	+0.871 / -0.800	± 0.836
DataStat	+0.647 / -0.634	± 0.641	DataStat	+0.546 / -0.544	± 0.545	DataStat	+0.781 / -0.742	± 0.761
FullSyst	+0.951 / -0.644	± 0.797	FullSyst	+0.435 / -0.379	± 0.407	FullSyst	+0.387 / -0.300	± 0.343
Floating normalizations	+0.250 / -0.238	± 0.244	Floating normalizations	+0.105 / -0.145	± 0.125	Floating normalizations	+0.094 / -0.045	± 0.069
Multi Jet	+0.025 / -0.025	± 0.025	Multi Jet	+0.010 / -0.011	± 0.010	Multi Jet	+0.006 / -0.005	± 0.005
Modelling: single top	+0.038 / -0.051	± 0.045	Modelling: single top	+0.035 / -0.039	± 0.037	Modelling: single top	+0.019 / -0.007	± 0.013
Modelling: ttbar	+0.160 / -0.194	± 0.177	Modelling: ttbar	+0.091 / -0.112	± 0.101	Modelling: ttbar	+0.041 / -0.030	± 0.036
Modelling: W+jets	+0.045 / -0.047	± 0.046	Modelling: W+jets	+0.064 / -0.068	± 0.066	Modelling: W+jets	+0.051 / -0.049	± 0.050
Modelling: Z+jets	+0.274 / -0.215	± 0.245	Modelling: Z+jets	+0.183 / -0.184	± 0.183	Modelling: Z+jets	+0.060 / -0.041	± 0.051
Modelling: Diboson	+0.142 / -0.113	± 0.128	Modelling: Diboson	+0.126 / -0.125	± 0.125	Modelling: Diboson	+0.054 / -0.044	± 0.049
Modelling: VH	+0.749 / -0.248	± 0.499	Modelling: VH	+0.210 / -0.098	± 0.154	Modelling: VH	+0.259 / -0.156	± 0.208
Detector: lepton	+0.069 / -0.051	± 0.060	Detector: lepton	+0.024 / -0.023	± 0.024	Detector: lepton	+0.031 / -0.028	± 0.029
Detector: MET	+0.254 / -0.256	± 0.255	Detector: MET	+0.043 / -0.047	± 0.045	Detector: MET	+0.036 / -0.033	± 0.035
Detector: JET	+0.204 / -0.165	± 0.184	Detector: JET	+0.082 / -0.070	± 0.076	Detector: JET	+0.072 / -0.047	± 0.059
Detector: FTAG (b-jet)	+0.115 / -0.197	± 0.156	Detector: FTAG (b-jet)	+0.123 / -0.159	± 0.141	Detector: FTAG (b-jet)	+0.130 / -0.062	± 0.096
Detector: FTAG (c-jet)	+0.011 / -0.025	± 0.018	Detector: FTAG (c-jet)	+0.015 / -0.006	± 0.011	Detector: FTAG (c-jet)	+0.042 / -0.027	± 0.034
Detector: FTAG (l-jet)	+0.081 / -0.071	± 0.076	Detector: FTAG (l-jet)	+0.023 / -0.021	± 0.022	Detector: FTAG (l-jet)	+0.002 / -0.004	± 0.003
Detector: FTAG (extrap)	+0.006 / -0.002	± 0.004	Detector: FTAG (extrap)	+0.003 / -0.004	± 0.004	Detector: FTAG (extrap)	+0.006 / -0.005	± 0.005
Detector: PU	+0.046 / -0.046	± 0.046	Detector: PU	+0.003 / -0.005	± 0.004	Detector: PU	+0.020 / -0.009	± 0.015
Lumi	+0.057 / -0.017	± 0.037	Lumi	+0.027 / -0.003	± 0.015	Lumi	+0.046 / -0.015	± 0.030
MC stat	+0.457 / -0.318	± 0.388	MC stat	+0.198 / -0.201	± 0.199	MC stat	+0.223 / -0.219	± 0.221

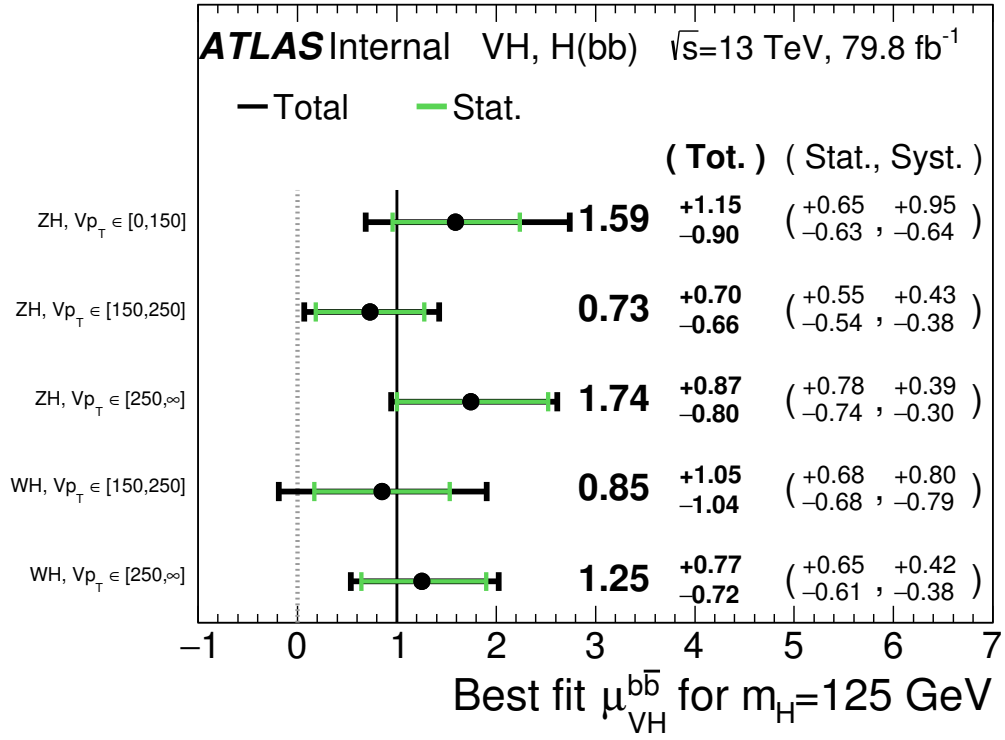


Figure 7.23 – Measured VH simplified template cross sections normalised by their SM predictions.

7.4 Prospects for the $VH, H \rightarrow b\bar{b}$ measurement at the HL-LHC

The LHC Run 3 will allow ATLAS and CMS to collect about 300 fb^{-1} of pp collisions with a maximum center-of-mass energy of 14 TeV by the end of 2023. After the end of the LHC Run 3, A high-luminosity (HL) phase (also called Phase-II) of the LHC [124] is planned to take place.

The HL-LHC will exploit an improved LHC injector complex and better collimation and focusing quadrupoles to deliver a (constant, levelled) peak luminosity of $5 - 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, leading to an integrated luminosity of $250 - 350 \text{ fb}^{-1}$ per year at $\sqrt{s} = 14 \text{ TeV}$, with the goal of $3000 - 4000 \text{ fb}^{-1}$ in about a dozen years after the upgrade. While work on the injector complex has already started and should be completed in the long shutdown (LS2, 2019–2020) between Run 2 and Run 3, installation of the new focusing magnets and other LHC upgrades will take place in the long shutdown (LS3, 2024–2025) after Run 3. The larger instantaneous luminosity will pose challenges to the ATLAS detector, in terms of radiation hardness and of occupancy in the detectors. Event reconstruction will have to deal with an average number of 140–200 pile-up interactions per bunch crossing. For these reasons, parallel to the LHC upgrade work, also the ATLAS detector will undergo important upgrade activities (in particular, with a completely new charged particle tracker) with the new hardware being installed in LS3, in order to be ready for commissioning at the beginning of 2026 and then for high-intensity collision data-taking later on.

A study of the physics case of the HL-LHC upgrade with an updated ATLAS detector was performed for the 2012 update of the European Strategy for Particle Physics [125] and in the ATLAS Phase-II upgrade Letter of Intent [126]. One of the main opportunities provided by the very large data set produced by the HL-LHC is the precise measurement of the Higgs boson properties. If the Higgs boson discovered in 2012, and whose mass is known to better than 2 per mille accuracy, is that of the Standard Model, then its properties are predicted very precisely. On the other hand, experimentally, the results obtained until today (which are all in agreement with the predictions) are affected by uncertainties of at least 12–14% and often larger. Precise measurements in the Higgs sector are therefore a high priority in the future programme of particle physics.

A comprehensive study of the prospects for measuring Higgs boson production cross sections times branching ratios, and couplings to individual fermions and bosons, was presented by the ATLAS Collaboration at the ECFA HL-LHC workshop in 2014 [127]. In particular, the study included a study of the expected sensitivity to $VH, H \rightarrow b\bar{b}$ with 3000 fb^{-1} of 14 TeV pp collisions with an assumed number of pile-up events per bunch crossing of 140. The analysis used particle-level simulations, corrected with parametrisations of the response (efficiency, resolution) of the upgraded ATLAS detector to final state particles as determined from studies of ATLAS full simulation events samples. The projected μ (signal strength) uncertainties are shown in Figure 7.24.

The $VH, H \rightarrow b\bar{b}$ prospect studies were performed based on an analysis strategy similar to the one performed in Run 1, through a fit to the m_{bb} distribution, using only the 1 and 2-lepton channels. Systematic uncertainties were projected based on Run 1 experience, with extrapolations accounting for recent improvements in analysis techniques and in calibrations. Two scenarios were considered, with (i) 10% jet energy scale uncertainties and (ii) 5% jet energy scale uncertainties. Projections were provided with current theoretical uncertainties and without theoretical uncertainties, to show the ultimate experimental sensitivity in case of import progress on the theory side that would render the measurements basically unaffected by uncertainties in the calculations. The results are shown in Figure 7.25.

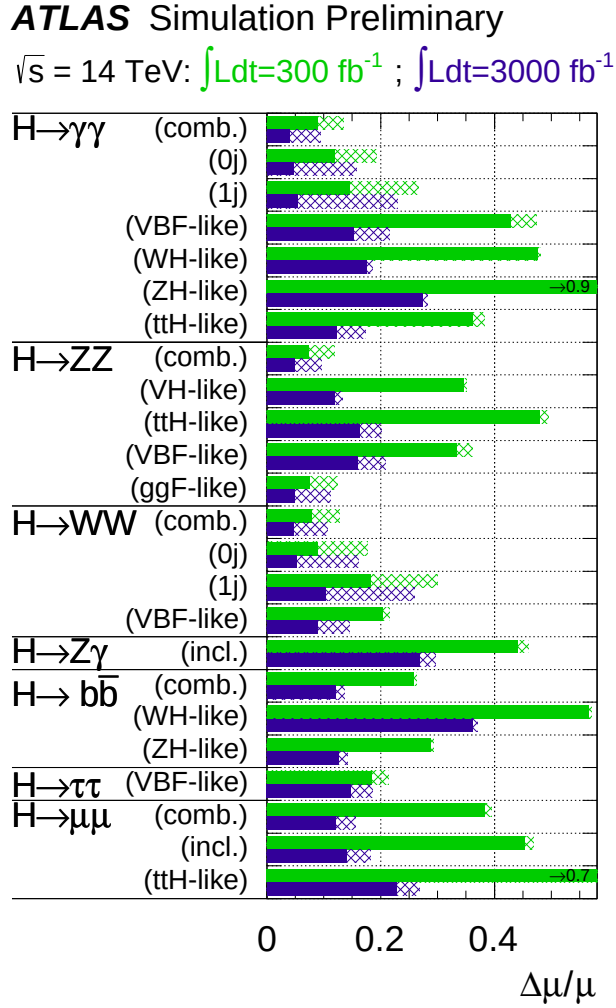


Figure 7.24 – Relative uncertainty on the signal strength μ for various Higgs boson final states, assuming a SM Higgs boson with a mass of 125 GeV expected with 300 fb^{-1} (green) or 3000 fb^{-1} (blue) of 14 TeV HL-LHC data, according to studies performed in 2014. The hashed areas indicate the increase of the estimated error due to systematic uncertainties on theory calculations available when the study was performed. The abbreviation “(comb.)” indicates that the precision on μ is obtained from the combination of the measurements from the different experimental sub-categories for the same final state, while “(incl.)” indicates that the measurement from the inclusive analysis was used.

		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{\text{Stats}}$ error	+0.07 – 0.06	+0.09 – 0.09	+0.05 – 0.05
Theory-only	$\hat{\mu}_{\text{Theory}}$ error	+0.09 – 0.07	+0.07 – 0.08	+0.07 – 0.07
	Significance	2.7	8.4	8.8
Scenario I	$\hat{\mu}_{\text{w/Theory}}$ error	+0.37 – 0.36	+0.15 – 0.15	+0.14 – 0.14
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.36 – 0.36	+0.14 – 0.12	+0.12 – 0.12
	Significance	4.7	-	9.6
Scenario II	$\hat{\mu}_{\text{w/Theory}}$ error	+0.23 – 0.22	-	+0.13 – 0.13
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.21 – 0.21	-	+0.11 – 0.11
	Significance	-	-	-

Figure 7.25 – Expected signal sensitivity as well as the precision on the signal strength measurement for VH , $H \rightarrow b\bar{b}$ with $m_H = 125$ GeV for the one-lepton, two-lepton and combined searches with 3000 fb^{-1} with $\langle\mu\rangle_{\text{pu}} = 140$ after including the perspective of a more performant analysis.

The next update of the European Strategy for Particle Physics will take place in 2019, with the goal of reaching a decision endorsed by the CERN Council in May 2020. For this reason, the ATLAS and CMS Collaborations are re-evaluating their projections for the HL-LHC sensitivity of various physics measurements and searches in order to provide updated inputs based on the latest advances in such analyses (building on the experience gained with Run 2 data) as well as the latest developments in detector R&Ds towards the Phase-II upgrade. A public document (“yellow report”) is being prepared by ATLAS, with a full chapter dedicated to SM Higgs boson couplings measurements. It is in this context that I worked on HL-LHC extrapolation studies of the VH , $H \rightarrow b\bar{b}$ sensitivity based on the experience gained with the Run 2 analysis that led to the $H \rightarrow b\bar{b}$ observation. The study was performed in the following way.

As in the Run 2 analysis, the VH , $H \rightarrow b\bar{b}$ signal cross sections are determined through fits to a discriminant variable, which is in the signal regions a boosted decision tree, called BDT_{VH} , that uses as input several kinematic quantities characterising the selected events; in the control regions, the discriminating variables are either the dijet invariant mass m_{bb} or the event yield. The same BDT_{VH} or m_{bb} distributions as used in the fit to the 13 TeV data are used, but their normalisations (and the yields used to fit some control regions) are increased to account for the larger integrated luminosity (3000 fb^{-1} instead of 79.8) and production cross sections due to the higher pp center-of-mass energy ($\sqrt{s} = 14$ TeV instead of 13 TeV). Using the most up-to-date calculations, the WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ cross sections were rescaled by factors of 1.102, 1.105, and 1.176 respectively, while the background was rescaled by an average factor of 1.1.

The extrapolation assumes that object reconstruction efficiencies, resolutions and fake rates are similar between Run 2 and the high-luminosity phase. This assumes that the ATLAS upgraded detectors at the HL-LHC, with their improved intrinsic performance, will be able to provide similar performance to the current ATLAS detector in events with much larger pile-

up. Such assumptions are motivated by the guiding lines that have permeated all R&D studies on the ATLAS upgrade and on simulations of the proposed upgraded detectors that seem to indicate that such target can be achieved.

Two different scenarios for the extrapolation of the experimental and modelling systematic uncertainties have been considered. The first scenario, denoted S1, assumes the same values of the uncertainties as those used in the Run 2 analysis. In the second scenario, denoted S2, a reduction is assumed of the systematic uncertainties, both of experimental and theoretical origin. The reduction factors have been discussed and agreed upon between ATLAS, CMS and the theory community, based on guesses of how large the improvements might be in 20 years on both the theory side and when exploiting the full potential of the HL-LHC data to constrain backgrounds and determine with data control samples the detector performance, thus relying as little as possible on simulations. This made it possible for ATLAS and CMS to define a common, consistent strategy for the HL/HE-LHC CERN Yellow Report to be submitted at the end 2018. Theory uncertainties, except for the already small uncertainty on the $H \rightarrow b\bar{b}$ branching ratio, have been scaled down by a factor two. Several experimental uncertainties have also been reduced (typically by factors between 2 and 3) or neglected, as shown in Table 7.10. Systematic uncertainties due to limited MC statistic are removed, in the assumption that most of the inputs of the analysis will be constrained by making use of large enough data control samples.

Two type of fits are performed: a fit in which there is a single parameter of interest (POI), the inclusive signal strength μ_{VH} ,

$$\mu = \frac{\sigma(VH) \cdot BR(H \rightarrow b\bar{b})}{\sigma^{SM}(VH) \cdot BR^{SM}(H \rightarrow b\bar{b})}$$

, and a fit in which there are three POIs, the signal strengths μ_{qqWH} , μ_{qqZH} and μ_{ggZH} of the three signal production processes, $qq \rightarrow WH$, $qq \rightarrow ZH$ and $gg \rightarrow ZH$. In both fits the denominator in the signal strength includes theoretical uncertainties on the predictions. Fits are also performed in which the POI is the product of the cross section times $H \rightarrow b\bar{b}$ branching ratio, removing theoretical uncertainties on $\sigma^{SM}(VH) \cdot BR^{SM}(H \rightarrow b\bar{b})$. The results of such fits are more representative of the experimental sensitivity to the VH , $H \rightarrow b\bar{b}$ cross section, and are easier to compare to SM predictions in case for instance of improved future calculations. The inputs to the fits are the yields, m_{bb} or BDT_{VH} distributions from the simulations used in the Run 2 analysis, scaled by the data/MC scaling factors observed in the fit to Run 2 data and further multiplied by the cross-section and luminosity ratios.

In the 1-POI fit to determine the inclusive signal strength μ_{VH} (with $H \rightarrow b\bar{b}$), the expected scenario S1 result is:

$$\mu_{VH} = 1.000^{+0.024}_{-0.023}(stat.)^{+0.085}_{-0.077}(syst.),$$

while with the improved uncertainties of scenario S2, the expected result is:

$$\mu_{VH} = 1.000^{+0.024}_{-0.024}(stat.)^{+0.053}_{-0.051}(syst.)$$

where the first uncertainty is the statistical one and the second is the systematic one. The measurement is limited by the systematic uncertainties, and in particular those related to the modeling of the VH signal, and thus treatly benefit from the reduced systematic uncertainties of scenario S2. Figure 7.26 shows the ranking of top 15 most important systematic uncertainties for scenario S2.

Table 7.10 – Scale factors applied to reduce the prior systematic uncertainties for the HL-LHC VH , $H \rightarrow b\bar{b}$ from scenario S1 to scenario S2 projections. The electron and muon related systematic uncertainties are not reduced since they have negligible impacts on the μ measurement. The systematic uncertainties denoted with “removed” are considered not to be applicable to the HL-LHC analysis and they are not included in the fit. The systematic uncertainties denoted with “-” are kept the same as in the Run 2 analysis.

Nuisance parameter	Scenario 1	Scenario 2
MC statistics	removed	removed
Luminosity	-	2% reduced to 1%
JET_EffectiveNP_2	-	0.5
JET_EtaIntercalibration_*	-	removed
JET_Pileup_*	-	removed
JET_PunchThrough_*	-	removed
JET_SingleParticle_HighPt	-	removed
JET_JER_SINGLE_NP	-	0.5
TAU_SME_TES_INSITU	-	0.6
FT_EFF_Eigen_B_[1-3]	-	1/3
FT_EFF_Eigen_C_[1-3]	-	1/3
FT_EFF_Eigen_L_[1-5]	-	0.5
Shape syst. of Stopt & StopWt	-	0.5
Shape syst. of ttbar	-	0.5
Shape syst. of VV from ME	-	removed
Shape syst. of W+jets	-	0.5
Shape syst. of Z+jets	-	0.5
Shape syst. of Multijet (MJ)	-	0.5
Shape syst. of VH signal from QCDscale	-	0.5
Shape syst. of VH signal from PDF	-	0.5
Shape syst. of VH signal from UEPS	-	0.5
Shape syst. of VH signal from NLOEWK	-	0.5
Theory of backgrounds	-	0.5
Theory acceptance of signal from QCD scale	-	0.5
Theory acceptance of signal from PDF	-	0.5
Theory acceptance of signal from UEPS	P8-H7 diff. dropped	P8-H7 diff. dropped
Theory XS of $qqVH$ from QCD scale	-	0.5
Theory XS of $ggZH$ from QCD scale	-	27% reduced to 15%
Theory XS of signal from PDF	-	0.5

The three-POI fit to determine the WH , $qq \rightarrow ZH$, and $gg \rightarrow ZH$ signal strenghts yields

$$\mu_{WH} = 1.000^{+0.041}_{-0.041}(stat.)^{+0.038}_{-0.035}(exp.)^{+0.090}_{-0.076}(sig.)^{+0.107}_{-0.100}(bkg)^{+0.022}_{-0.018}(lumi),$$

$$\mu_{qqZH} = 1.000^{+0.089}_{-0.088}(stat.)^{+0.056}_{-0.054}(exp.)^{+0.064}_{-0.057}(sig.)^{+0.053}_{-0.052}(bkg)^{+0.017}_{-0.015}(lumi),$$

$$\mu_{ggZH} = 1.000^{+0.307}_{-0.307}(stat.)^{+0.228}_{-0.203}(exp.)^{+0.503}_{-0.191}(sig.)^{+0.223}_{-0.197}(bkg)^{+0.027}_{-0.016}(lumi),$$

in scenario S1, while the improved uncertainties of scenario S2 give:

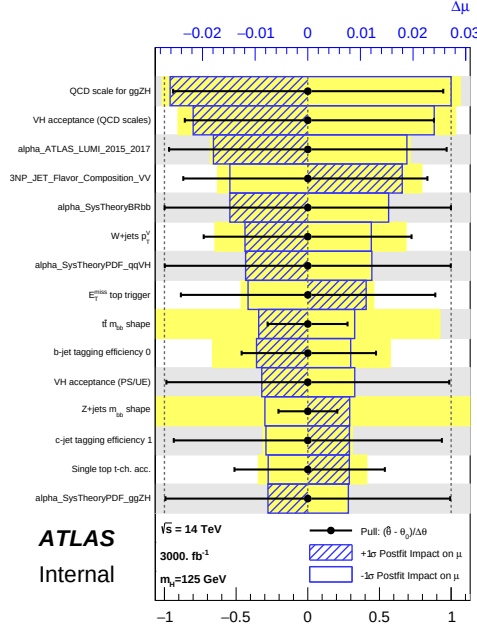


Figure 7.26 – Ranking of the 15 most important systematic uncertainties according to their post-fit impact on the $VH \rightarrow b\bar{b}$ signal strength at scenario S2 of the HL-LHC extrapolation assumption.

$$\begin{aligned}\mu_{WH} &= 1.000^{+0.041}_{-0.041}(\text{stat.})^{+0.026}_{-0.024}(\text{exp.})^{+0.051}_{-0.044}(\text{sig.})^{+0.072}_{-0.069}(\text{bkg})^{+0.005}_{-0.010}(\text{lumi}), \\ \mu_{qqZH} &= 1.000^{+0.089}_{-0.088}(\text{stat.})^{+0.057}_{-0.055}(\text{exp.})^{+0.035}_{-0.030}(\text{sig.})^{+0.048}_{-0.045}(\text{bkg})^{+0.008}_{-0.006}(\text{lumi}), \\ \mu_{ggZH} &= 1.000^{+0.307}_{-0.307}(\text{stat.})^{+0.192}_{-0.190}(\text{exp.})^{+0.250}_{-0.114}(\text{sig.})^{+0.182}_{-0.181}(\text{bkg})^{+0.026}_{-0.023}(\text{lumi}),\end{aligned}$$

as shown in Figure 7.27.

The ranking of the top 15 most important systematic uncertainties on the signal strengths for the three production mode $qq \rightarrow WH$, $qq \rightarrow ZH$, $gg \rightarrow ZH$ in scenario S2 in the 3-POI fit, is shown in Figure 7.28.

Finally, the three cross sections for WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production times the $H \rightarrow b\bar{b}$ branching ratio are determined from a 3-POI fit similar to the one discussed in the previous section, but in which the signal distribution (for each of the three production modes) is expressed as the product of its production cross section times branching ratio to be measured, and the acceptance times efficiency from the simulation. Theoretical uncertainties related to the signal thus affect only the acceptance times efficiency prediction.

The measured product of the cross-section times the $H \rightarrow b\bar{b}$ branching ratio for each signal, are the following, where the uncertainties outside (inside) the parentheses correspond to scenario

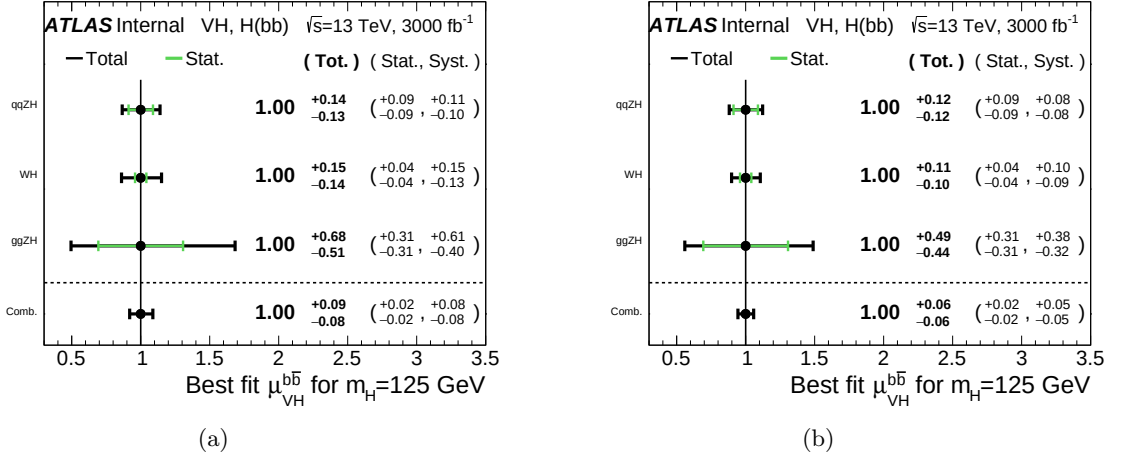


Figure 7.27 – The fitted values of the Higgs boson signal strength parameter μ for the WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ processes and their combination expected with 3000 fb^{-1} of pp collisions at the HL-LHC in the (a) scenario S1 and (b) scenario S2 extrapolations. The individual μ values for the three processes are obtained from a simultaneous fit in which the signal strength parameter for each of the WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ processes are floating independently.

S1 (S2):

$$\begin{aligned}
 \sigma(WH) \times \text{B}(H \rightarrow b\bar{b}) &= 0.877^{+0.131}_{-0.121}^{(+0.091)} \text{ pb} \\
 &= 0.877^{+0.036}_{-0.036}^{(+0.036)} (\text{stat}) \\
 &\quad +0.035^{+0.024}_{-0.032} (\text{exp}) \\
 &\quad +0.079^{+0.042}_{-0.063} (\text{sig}) \\
 &\quad +0.095^{+0.063}_{-0.089} (\text{bkg}) \\
 &\quad +0.024^{+0.016}_{-0.017} (\text{lumi}) \text{ pb}
 \end{aligned} \tag{7.17}$$

$$\begin{aligned}
 \sigma(qq \rightarrow ZH) \times \text{B}(H \rightarrow b\bar{b}) &= 0.488^{+0.067}_{-0.064}^{(+0.059)} \text{ pb} \\
 &= 0.488^{+0.043}_{-0.043}^{(+0.043)} (\text{stat}) \\
 &\quad +0.028^{+0.028}_{-0.025} (\text{exp}) \\
 &\quad +0.029^{+0.013}_{-0.025} (\text{sig}) \\
 &\quad +0.026^{+0.023}_{-0.023} (\text{bkg}) \\
 &\quad +0.011^{+0.001}_{-0.006} (\text{lumi}) \text{ pb}
 \end{aligned} \tag{7.18}$$

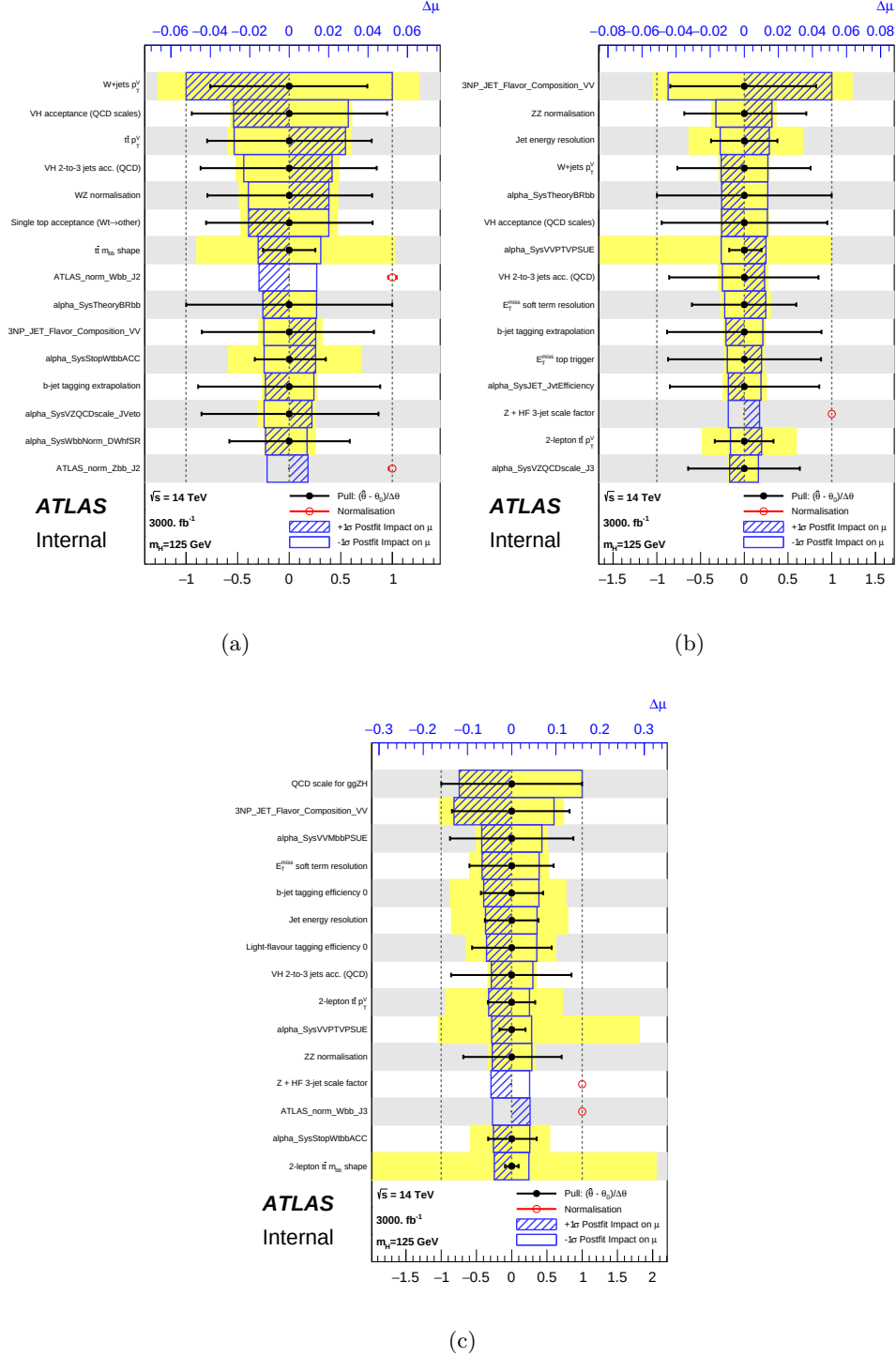


Figure 7.28 – Ranking of the 15 most important systematic uncertainties according to their post-fit impact on the (a) $WH, H \rightarrow b\bar{b}$, (b) $qq \rightarrow ZH, H \rightarrow b\bar{b}$, (c) $gg \rightarrow ZH, H \rightarrow b\bar{b}$ signal strengths in scenario S2 of the HL-LHC extrapolation.

$$\begin{aligned}
 \sigma(gg \rightarrow ZH) \times \text{B}(H \rightarrow b\bar{b}) &= 0.084 \begin{matrix} +0.042 \\ -0.041 \end{matrix} \begin{matrix} (+0.036 \\ -0.036 \end{matrix} \text{pb} \\
 &= 0.084 \begin{matrix} +0.026 \\ -0.026 \end{matrix} \begin{matrix} (+0.026 \\ -0.026 \end{matrix} (\text{stat}) \\
 &\quad +0.018 \begin{matrix} (+0.016 \\ -0.016 \end{matrix} (\text{exp}) \\
 &\quad +0.015 \begin{matrix} (+0.008 \\ -0.013 \end{matrix} (\text{sig}) \\
 &\quad +0.017 \begin{matrix} (+0.015 \\ -0.018 \end{matrix} (\text{bkg}) \\
 &\quad +0.004 \begin{matrix} (+0.002 \\ -0.003 \end{matrix} (\text{lumi}) \text{pb}
 \end{aligned} \tag{7.19}$$

These numbers are translated in relative precision in Table 7.11.

Table 7.11 – Expected results for WH , $qq \rightarrow ZH$ and $gg \rightarrow ZH$ production times the $H \rightarrow b\bar{b}$ branching ratio with 79.8fb^{-1} of Run 2 data and at the HL-LHC. Uncertainties are reported relative to the SM cross section at the corresponding center-of-mass energy. Two scenarios have been considered for the uncertainties in the HL-LHC extrapolation. The last column shows the theory uncertainty when fitting production mode signal strengths instead of cross sections.

Prod. mode	Scenario	$\frac{\Delta_{\text{tot}}}{\sigma_{\text{SM}}}$	$\frac{\Delta_{\text{stat}}}{\sigma_{\text{SM}}}$	$\frac{\Delta_{\text{exp}}}{\sigma_{\text{SM}}}$	$\frac{\Delta_{\text{bkg}}}{\sigma_{\text{SM}}}$	$\frac{\Delta_{\text{sig}}}{\sigma_{\text{SM}}}$	$\Delta\mu_{\text{theo,sig}}$
WH	Run 2, 79.8fb^{-1}	+0.462 −0.425	+0.272 −0.265	+0.157 −0.127	+0.224 −0.213	+0.176 −0.075	+0.180 −0.077
	HL-LHC w. Scenario S1	+0.149 −0.138	+0.041 −0.041	+0.040 −0.036	+0.108 −0.101	+0.090 −0.072	+0.090 −0.076
	HL-LHC w. Scenario S2	+0.104 −0.101	+0.041 −0.041	+0.027 −0.027	+0.072 −0.070	+0.048 −0.042	+0.051 −0.044
$qq \rightarrow ZH$	Run 2, 79.8fb^{-1}	+0.667 −0.629	+0.578 −0.562	+0.129 −0.101	+0.143 −0.126	+0.175 −0.105	+0.180 −0.105
	HL-LHC w. Scenario S1	+0.138 −0.132	+0.089 −0.088	+0.057 −0.052	+0.053 −0.047	+0.059 −0.051	+0.064 −0.057
	HL-LHC w. Scenario S2	+0.121 −0.118	+0.089 −0.088	+0.057 −0.056	+0.048 −0.046	+0.027 −0.027	+0.035 −0.030
$gg \rightarrow ZH$	Run 2, 79.8fb^{-1}	+2.629 −2.608	+2.105 −2.105	+0.606 −0.677	+1.012 −1.037	+0.658 −0.454	+1.269 −0.645
	HL-LHC w. Scenario S1	+0.498 −0.488	+0.307 −0.307	+0.212 −0.215	+0.208 −0.210	+0.182 −0.154	+0.503 −0.199
	HL-LHC w. Scenario S2	+0.431 −0.432	+0.307 −0.307	+0.185 −0.190	+0.174 −0.182	+0.090 −0.081	+0.250 −0.114

Higgs boson production in association with a vector boson followed by a decay to $b\bar{b}$ is thus expected to be measured with 10–12% accuracy at the HL-LHC in scenario S2 for qq production, and about 40% accuracy for $gg \rightarrow ZH$ production. This should lead to a measurement of the Higgs boson coupling to the bottom quark with few % relative uncertainty. In addition, the large data sample available should allow much more differential measurements, including most likely a full determination of the stage-1 simplified template VH cross sections, going possibly to even more granular phase space regions. The projection of the sensitivity of the VH , $H \rightarrow b\bar{b}$

analysis to the stage-1 VH STXS with the HL-LHC dataset would provide valuable additional information for these perspective studies, but is beyond the scope of this thesis manuscript.

Chapter 8

Conclusion

In this manuscript I have presented two measurements, performed using data collected by the ATLAS experiment at the LHC: the measurement of the b -jet identification (“tagging”) efficiency [22], and the measurement of the cross section times branching ratio of a Higgs boson produced in association with a vector boson $V = W, Z$ and decaying to b -quark pairs, VH , $H \rightarrow b\bar{b}$ [23, 24].

The b -tagging efficiency of a multivariate identification algorithm widely used in ATLAS (MV2c10) has been measured in data for several “working points” and different jet clustering algorithms exploited in different ATLAS analyses. The measurement is using a control sample enriched in b -jets produced in $t\bar{t}$ events, selected in the 36 fb^{-1} of pp collisions collected at a center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ by the ATLAS detector. To suppress backgrounds, a final state consistent with $t\bar{t} \rightarrow e^\pm \nu \mu^\mp \nu b\bar{b}$ is selected. A boosted decision tree (BDT), based only on kinematic and topological event variables, is used to select events in which the two selected jets are from b quarks, reducing the contamination from events in which only one b -jet is reconstructed in the detector acceptance.

The b -tagging efficiencies have been measured as a function of the jet transverse momentum (p_T), pseudorapidity (η), and of the average number of pile-up collisions (μ). The efficiencies measured in data have been compared to those predicted from the simulation, and simulation-to-data efficiency scale factors have been determined, that can then be used to correct the simulation of physics processes with identified b -jets in the final state. No significant dependence of the scale factors on the jet pseudorapidity and on the average number of interaction per bunch-crossing was observed, with maximum variation of 1% over the range $1 < \mu < 50$ and of 5% for $|\eta|$ varying between 0 and 2.5.

The efficiency scale factors are close to unity, with total uncertainty ranging between 2% and 12%; the uncertainty is dominated by the limited number of selected jets at the low and high- p_T ends of the spectra, while it is dominated by systematic uncertainties in the intermediated p_T range, relevant for the $H \rightarrow b\bar{b}$ searches. The leading source of systematic uncertainty is the modelling of the flavour of the jets in $t\bar{t}$ events, and the use of a BDT to increase the b -jet purity of the control sample has significantly reduced such uncertainty. In the future, with the data collected in 2017 and 2018, which will correspond to about 115 fb^{-1} of pp collisions at 13 TeV, it will be possible to increase the number of jet probes, in order to improve the measurement at low and high p_T , and to tighten the selection criteria in the intermediate p_T range to select a control sample even purer in b -jets and thus less affected by systematic uncertainties than the current one.

The measurement of the VH production cross section times $H \rightarrow b\bar{b}$ branching ratio has been performed twice, first using 36 fb^{-1} of 13 TeV pp collisions collected in 2015 and 2016, and later

adding 44 fb^{-1} of 13 TeV pp collisions collected in 2017. The results, published respectively in 2017 and 2018, provide a strong evidence of such process, with excesses of events with respect to the Standard Model (SM) background expectations that have observed significances of 3.5 standard deviations and of 4.9 standard deviations, respectively. The signal strength, defined as the ratio between the measured cross section times branching ratio and the SM prediction, is measured with the 2015–2017 dataset to be $\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16$ (stat.) $^{+0.21}_{-0.19}$ (syst.), in good agreement with the SM prediction of 1. The uncertainty is dominated by signal and background modelling uncertainties, that need to be improved in the future by exploiting larger data samples to constrain directly the shape of the background, and through improved theory predictions for the signal. The leading source of experimental uncertainty (6%) is the b -tagging efficiency uncertainty for b -jets, which makes it important to work on further improving the determination of the b -tagging efficiency in the future.

A combination of the results of the VH , $H \rightarrow b\bar{b}$ results based on 80 fb^{-1} of 13 TeV collisions with the results of the same analysis performed on data collected at lower (7 and 8 TeV) center-of-mass energies in 2011 and 2012 and with those of searches for $H \rightarrow b\bar{b}$ decays in other Higgs boson production modes (vector-boson fusion, associated production with a top-quark pair) have led to the observation of the $H \rightarrow b\bar{b}$ decay with a significance of 5.4 standard deviations, and a signal strength $\mu^{bb} = 1.01 \pm 0.20 = 1.01 \pm 0.12$ (stat.) $^{+0.16}_{-0.15}$ (syst.). This establishes unequivocally the coupling of the Higgs boson to down-type quarks and the decay of the Higgs boson to the $b\bar{b}$ final state which, in the Standard Model, is predicted to be the preferred one, with a branching ratio of about 58%. The measured branching ratio – determined assuming SM cross sections for the different production modes – is in agreement with the SM prediction within a 20% relative uncertainty.

A combination of the results of the VH , $H \rightarrow b\bar{b}$ results based on 80 fb^{-1} of 13 TeV collisions with the results of searches for the same production mode on the same amount of data in the diphoton and $ZZ^* \rightarrow 4\ell$ Higgs boson final states has led to the observation of VH production with a significance of 5.3 standard deviations, and a signal strength $\mu^{VH} = 1.13^{+0.24}_{-0.23} = 1.13 \pm 0.15$ (stat.) $^{+0.18}_{-0.17}$ (syst.) in good agreement with the SM.

These results, together with those by the CMS Collaboration and the results of other searches in different production modes and final states, confirm the validity of the Standard Model predictions in the Higgs boson sector: all main Higgs boson production modes at the LHC (gluon fusion, vector-boson fusion, VH and $t\bar{t}H$ associated productions), as well as several decays to either bosons ($\gamma\gamma$, ZZ^* , WW) or fermions ($b\bar{b}$, $\tau\tau$), are now firmly established and agree with the predictions for a Higgs boson with a mass (as measured with $\gamma\gamma$ and $ZZ^* \rightarrow 4\ell$ decays) of 125.09 GeV. For the future, improved measurements of these decays are needed to further stress the SM prediction, as well as measurements of the branching ratios of rarer decay modes like $Z\gamma$ and – particularly interesting as it would probe the couplings to second-generation fermions – $\mu\mu$.

Now that VH production and $H \rightarrow b\bar{b}$ decays are observed, the VH , $H \rightarrow b\bar{b}$ analysis has to be improved and refined in order to do more fiducial measurements, that are less affected by theory uncertainties, and more granular ones, in order to exploit the increasingly larger samples to separately measure the cross sections of the different VH processes ($qq \rightarrow WH$, $qq \rightarrow ZH$, $gg \rightarrow ZH$) and to probe phase space regions that are more sensitive to physics beyond the Standard Model, such as production of V and Higgs bosons at high- p_T . This is the goal of the “simplified template cross section” measurement that I have performed with 80 fb^{-1} of 13 TeV pp collisions. The results are the first attempt to measure VH “simplified template” cross sections beyond the so-called “stage-0” approach in which the inclusive cross section in a fiducial Higgs boson pseudorapidity region $|y_H| < 2.5$ is measured. To obtain these results, and compare them

to SM predictions, theory uncertainties had to be computed for the first time, implementing the recommendations of the theoretical community taking part to the LHC cross section working group. The results indicate that the data are still not enough to perform measurements with relative uncertainties significantly smaller than 100%, as soon as one starts to divide the phase space in a non trivial number of bins. However, the results could still be used to infer limits on new physics scenarios in an effective field theory (EFT) approach; this study is ongoing, but it is expected that these results can constrain the coefficients of dimension-6 operators of the EFT lagrangian corresponding to anomalous HWW and HZZ couplings more than current measurements with $H \rightarrow ZZ$ or $H \rightarrow WW$ decays can.

Finally, the high-luminosity (HL) phase of the LHC, which will start in 2026, will allow collecting 3000 fb^{-1} of 14 TeV pp collisions. This sample, almost 40 times larger than the one used for the observation of the $H \rightarrow b\bar{b}$ decay presented in this thesis, will definitely allow for much more precise measurements of the Hbb coupling as well as of simplified template cross sections. Some seminal studies presented in this thesis, performed in the context of the update of the European particle physics strategy that will take place in 2019, use the results of the current measurement and reasonable guesstimates of the performance of the upgraded ATLAS detector at the HL-LHC to extrapolate the sensitivity to the WH and $(qq, gg \rightarrow) ZH$ cross sections. Measurements of the VH production cross sections times the branching ratio of $H \rightarrow b\bar{b}$ with 10–12% accuracy can be performed (for the qq -initiated processes) with an analysis similar to the current one; further refinements of the analysis to exploit the larger sample and introduce more event categories with better signal-to-background ratio or less affected by systematic uncertainties could further improve the precision of such measurements. Simplified template cross sections with a finer granularity and better accuracy than those presented in this manuscript will also be measured (though the expected sensitivity at the HL-LHC to such cross sections has not been estimated in this manuscript), significantly extending the constraining power and the sensitivity to new physics of the $V(\rightarrow \text{leptons}) + H(\rightarrow b\bar{b})$ final state.

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Bibliography

- [1] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, [Phys. Lett. **12** \(1964\) 132](#).
- [2] P. W. Higgs, *Broken symmetries and the masses of gauge bosons*, [Phys. Rev. Lett. **13** \(1964\) 508](#).
- [3] G. Guralnik, C. Hagen, and T. Kibble, *Global conservation laws and massless particles*, [Phys. Rev. Lett. **13** \(1964\) 585](#).
- [4] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, [Phys. Rev. Lett. **13** \(1964\) 321](#).
- [5] S. L. Glashow, *Partial Symmetries of Weak Interactions*, [Nucl. Phys. **22** \(1961\) 579](#).
- [6] S. Weinberg, *A Model of Leptons*, [Phys. Rev. Lett. **19** \(1967\) 1264](#).
- [7] A. Salam, in *Elementary Particle Theory*, p. 367. Almqvist and Wiksell, Stockholm, 1968.
- [8] S. Glashow, J. Iliopoulos, and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, [Phys. Rev. D **2** \(1970\) 1285](#).
- [9] M. Gell-Mann and Y. Neeman, *The Eight Fold Way*, Benjamin, New York, 1964.
- [10] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, [JINST **3** \(2008\) S08003](#).
- [11] CMS Collaboration, *The CMS experiment at the CERN LHC*, [JINST **3** \(2008\) S08004](#).
- [12] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, [Phys. Lett. B **716** \(2012\) 1–29](#), [arXiv:1207.7214 \[hep-ex\]](#).
- [13] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, [Phys. Lett. B **716** \(2012\) 30–61](#), [arXiv:1207.7235 \[hep-ex\]](#).
- [14] ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, [Phys. Lett. B **726** \(2013\) 120](#), [arXiv:1307.1432 \[hep-ex\]](#).
- [15] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*, [Phys. Lett. B **726** \(2013\) 88](#), [arXiv:1307.1427 \[hep-ex\]](#).

- [16] CMS Collaboration, *Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **06** (2013) 081, [arXiv:1303.4571 \[hep-ex\]](#).
- [17] ATLAS and CMS Collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **08** (2016) 045, [arXiv:1606.02266 \[hep-ex\]](#).
- [18] CDF, D0 Collaboration, T. Aaltonen et al., *Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron*, *Phys. Rev. Lett.* **109** (2012) 071804, [arXiv:1207.6436 \[hep-ex\]](#).
- [19] ATLAS Collaboration, *Search for the $b\bar{b}$ decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector*, *JHEP* **01** (2015) 069, [arXiv:1409.6212 \[hep-ex\]](#).
- [20] CMS Collaboration, *Measurement of diffractive dissociation cross sections in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. D* **92** (2015) 012003, [arXiv:1503.08689 \[hep-ex\]](#).
- [21] ATLAS Collaboration, *Expected performance of the ATLAS b-tagging algorithms in Run-2*, ATL-PHYS-PUB-2015-022 (2015) . <https://cds.cern.ch/record/2037697>.
- [22] ATLAS Collaboration, *Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV*, *JHEP* **08** (2018) 089, [arXiv:1805.01845 \[hep-ex\]](#).
- [23] ATLAS Collaboration, *Evidence for the $H \rightarrow b\bar{b}$ decay with the ATLAS detector*, *JHEP* **12** (2017) 024, [arXiv:1708.03299 \[hep-ex\]](#).
- [24] ATLAS Collaboration, *Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector*, *Phys. Lett. B* **786** (2018) 59, [arXiv:1808.08238 \[hep-ex\]](#).
- [25] CMS Collaboration, *Observation of Higgs boson decay to bottom quarks*, *Phys. Rev. Lett.* **121** (2018) 121801, [arXiv:1808.08242 \[hep-ex\]](#).
- [26] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, CERN-2011-002 (CERN, Geneva, 2011) , [arXiv:1101.0593 \[hep-ph\]](#).
- [27] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, CERN-2012-002 (CERN, Geneva, 2012) , [arXiv:1201.3084 \[hep-ph\]](#).
- [28] LHC Higgs Cross Section Working Group, S. Heinemeyer, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, CERN-2013-004 (CERN, Geneva, 2013) , [arXiv:1307.1347 \[hep-ph\]](#).
- [29] LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, CERN-2017-002-M (2016) , [arXiv:1610.07922 \[hep-ph\]](#).
- [30] ATLAS Collaboration, *Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, [arXiv:1802.04146 \[hep-ex\]](#).

-
- [31] ATLAS Collaboration, *Measurements of Higgs boson properties in the diphoton decay channel using 80 fb^{-1} of pp collision data at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, ATLAS-CONF-2018-028 (2018) . <https://cds.cern.ch/record/2628771>.
 - [32] CMS Collaboration, *Measurement of inclusive and differential Higgs boson production cross sections in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , [arXiv:1807.03825](https://arxiv.org/abs/1807.03825) [[hep-ex](#)].
 - [33] ATLAS Collaboration, *Measurement of the Higgs boson coupling properties in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, **JHEP** **03** (2018) 095, [arXiv:1712.02304](https://arxiv.org/abs/1712.02304) [[hep-ex](#)].
 - [34] ATLAS Collaboration, *Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, **JHEP** **10** (2017) 132, [arXiv:1708.02810](https://arxiv.org/abs/1708.02810) [[hep-ex](#)].
 - [35] ATLAS Collaboration, *Measurements of the Higgs boson production, fiducial and differential cross sections in the 4ℓ decay channel at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, ATLAS-CONF-2018-018 (2018) . <https://cds.cern.ch/record/2621479>.
 - [36] CMS Collaboration, *Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13\text{ TeV}$* , **JHEP** **11** (2017) 047, [arXiv:1706.09936](https://arxiv.org/abs/1706.09936) [[hep-ex](#)].
 - [37] CMS Collaboration, *Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s} = 13\text{ TeV}$* , CMS-PAS-HIG-18-001 (2018) . <https://cds.cern.ch/record/2621419>.
 - [38] ATLAS Collaboration, *Measurement of gluon fusion and vector boson fusion Higgs boson production cross-sections in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, ATLAS-CONF-2018-004 (2018) . <https://cds.cern.ch/record/2308392>.
 - [39] CMS Collaboration, *Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13\text{ TeV}$* , Submitted to: Phys. Lett. (2018) , [arXiv:1806.05246](https://arxiv.org/abs/1806.05246) [[hep-ex](#)].
 - [40] ATLAS Collaboration, *Searches for the $Z\gamma$ decay mode of the Higgs boson and for new high-mass resonances in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, **JHEP** **10** (2017) 112, [arXiv:1708.00212](https://arxiv.org/abs/1708.00212) [[hep-ex](#)].
 - [41] CMS Collaboration, *Search for the decay of a Higgs boson in the $\ell\ell\gamma$ channel in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , Submitted to: JHEP (2018) , [arXiv:1806.05996](https://arxiv.org/abs/1806.05996) [[hep-ex](#)].
 - [42] ATLAS and CMS Collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, **Phys. Rev. Lett.** **114** (2015) 191803, [arXiv:1503.07589](https://arxiv.org/abs/1503.07589) [[hep-ex](#)].
 - [43] ATLAS Collaboration, *Measurement of the Higgs boson mass in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels with $\sqrt{s} = 13\text{ TeV}$ pp collisions using the ATLAS detector*, [arXiv:1806.00242](https://arxiv.org/abs/1806.00242) [[hep-ex](#)].

- [44] ATLAS Collaboration, *Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector*, *Eur. Phys. J. C* **75** (2015) no. 10, 476, [arXiv:1506.05669 \[hep-ex\]](#). [Erratum: *Eur. Phys. J. C* 76,no.3,152(2016)].
- [45] CMS Collaboration, *Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV*, *Phys. Rev. D* **92** (2015) no. 1, 012004, [arXiv:1411.3441 \[hep-ex\]](#).
- [46] ATLAS Collaborations, *Cross-section measurements of the Higgs boson decaying to a pair of tau leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2018-021 (2018) . <https://cds.cern.ch/record/2621794>.
- [47] CMS Collaboration, *Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector*, *Phys. Lett. B* **779** (2018) 283–316, [arXiv:1708.00373 \[hep-ex\]](#).
- [48] ATLAS Collaboration, *A search for the rare decay of the Standard Model Higgs boson to dimuons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, ATLAS-CONF-2018-026 (2018) . <http://cds.cern.ch/record/2628763>.
- [49] CMS Collaboration, *Search for the Higgs boson decaying to two muons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, CERN-EP-2018-165 (2018) . <https://cds.cern.ch/record/2631546>.
- [50] ATLAS Collaboration, *Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment*, ATLAS-CONF-2018-031 (2018) . <http://cds.cern.ch/record/2629412>.
- [51] CMS Collaboration, *Combined measurements of the Higgs boson’s couplings at $\sqrt{s} = 13$ TeV*, CMS-PAS-HIG-17-031 (2018) . <https://cds.cern.ch/record/2308127>.
- [52] ATLAS Collaboration, *Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector*, [arXiv:1806.00425 \[hep-ex\]](#).
- [53] CMS Collaboration, *Observation of $t\bar{t}H$ production*, *Phys. Rev. Lett.* **120** (2018) no. 23, 231801, [arXiv:1804.02610 \[hep-ex\]](#).
- [54] ATLAS Collaboration, *Combined measurement of differential and total cross sections in the $H \rightarrow \gamma\gamma$ and the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS detector*, [arXiv:1805.10197 \[hep-ex\]](#).
- [55] D. Kazakov, *Beyond the Standard Model’ 17*, [arXiv:1807.00148 \[hep-ph\]](#).
- [56] L. Evans and P. Bryant, *LHC Machine*, *JINST* **3** (2008) S08001.
- [57] ATLAS IBL Collaboration, B. Abbott et al., *Production and Integration of the ATLAS Insertable B-Layer*, *JINST* **13** (2018) no. 05, T05008, [arXiv:1803.00844 \[physics.ins-det\]](#).
- [58] T. Cornelissen, M. Elsing, S. Fleischmann, W. Liebig, E. Moyse, and A. Salzburger, *Concepts, Design and Implementation of the ATLAS New Tracking (NEWT)*, ATL-SOFT-PUB-2007-007 (2007) . <https://cds.cern.ch/record/1020106>.

-
- [59] ATLAS Collaboration, *Track Reconstruction Performance of the ATLAS Inner Detector at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2015-018 (2015) .
<https://cds.cern.ch/record/2037683>.
- [60] ATLAS Collaboration, *Impact Parameter Resolution*, 2015.
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2015-007>.
- [61] ATLAS Collaboration, *Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton-proton collisions at the LHC*, *Eur. Phys. J. C* **77** (2017) no. 5, 332, [arXiv:1611.10235](https://arxiv.org/abs/1611.10235) [[physics.ins-det](#)].
- [62] ATLAS Collaboration, *Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach*, ATL-PHYS-PUB-2017-022 (2017) . <https://cds.cern.ch/record/2298955>.
- [63] ATLAS Collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, *Eur. Phys. J. C* **77** (2017) 490, [arXiv:1603.02934](https://arxiv.org/abs/1603.02934) [[hep-ex](#)].
- [64] *Photon identification in 2015 ATLAS data*, ATL-PHYS-PUB-2016-014 (2016) .
<https://cds.cern.ch/record/2203125>.
- [65] ATLAS Collaboration, *Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data*, ATLAS-CONF-2016-024 (2016) .
<http://cds.cern.ch/record/2157687>.
- [66] M. Cacciari, G. P. Salam, and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063, [arXiv:0802.1189](https://arxiv.org/abs/0802.1189) [[hep-ph](#)].
- [67] ATLAS Collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **96** (2017) no. 7, 072002, [arXiv:1703.09665](https://arxiv.org/abs/1703.09665) [[hep-ex](#)].
- [68] ATLAS Collaboration, *Tagging and suppression of pileup jets with the ATLAS detector*, ATLAS-CONF-2014-018 (2014) . <https://cds.cern.ch/record/1700870>.
- [69] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s}=13$ TeV*, *Eur. Phys. J. C* **76** (2016) no. 5, 292, [arXiv:1603.05598](https://arxiv.org/abs/1603.05598) [[hep-ex](#)].
- [70] ATLAS Collaboration, *Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment for Run-2 of the LHC*, ATL-PHYS-PUB-2015-045 (2015) . <http://cds.cern.ch/record/2064383>.
- [71] ATLAS Collaboration, *Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2017-029 (2017) . <http://cds.cern.ch/record/2261772>.
- [72] ATLAS Collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, [arXiv:1802.08168](https://arxiv.org/abs/1802.08168) [[hep-ex](#)].

- [73] ATLAS Collaboration, *Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run*, ATL-PHYS-PUB-2016-012 (2016) . <https://cds.cern.ch/record/2160731>.
- [74] T. Sjöstrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 physics and manual*, **JHEP** **05** (2006) 026, [arXiv:hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175).
- [75] GEANT4 Collaboration, S. Agostinelli et al., *GEANT4 - a simulation toolkit*, **Nucl. Instrum. Meth. A** **506** (2003) 250–303.
- [76] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, **Eur. Phys. J. C** **C70** (2010) 823–874, [arXiv:1005.4568](https://arxiv.org/abs/1005.4568) [[physics.ins-det](#)].
- [77] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, **JHEP** **11** (2004) 040, [arXiv:hep-ph/0409146](https://arxiv.org/abs/hep-ph/0409146).
- [78] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, **JHEP** **11** (2007) 070, [arXiv:0709.2092](https://arxiv.org/abs/0709.2092) [[hep-ph](#)].
- [79] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, **JHEP** **06** (2010) 043, [arXiv:1002.2581](https://arxiv.org/abs/1002.2581) [[hep-ph](#)].
- [80] J. M. Campbell, R. K. Ellis, P. Nason, and E. Re, *Top-pair production and decay at NLO matched with parton showers*, **JHEP** **04** (2015) 114, [arXiv:1412.1828](https://arxiv.org/abs/1412.1828) [[hep-ph](#)].
- [81] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, et al., *New parton distributions for collider physics*, **Phys. Rev. D** **82** (2010) 074024, [arXiv:1007.2241](https://arxiv.org/abs/1007.2241) [[hep-ph](#)].
- [82] P. Z. Skands, *Tuning Monte Carlo Generators: The Perugia Tunes*, **Phys. Rev. D** **82** (2010) 074018, [arXiv:1005.3457](https://arxiv.org/abs/1005.3457) [[hep-ph](#)].
- [83] M. Czakon and A. Mitov, *Top++: A program for the calculation of the top-pair cross-section at hadron colliders*, **Comput. Phys. Commun.** **185** (2014) 2930, [arXiv:1112.5675](https://arxiv.org/abs/1112.5675) [[hep-ph](#)].
- [84] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W- or H-*, **Phys. Rev. D** **82** (2010) 054018, [arXiv:1005.4451](https://arxiv.org/abs/1005.4451) [[hep-ph](#)].
- [85] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, **JHEP** **07** (2014) 79, [arXiv:1405.0301](https://arxiv.org/abs/1405.0301) [[hep-ph](#)].
- [86] NNPDF Collaboration, R. D. Ball et al., *Parton distributions for the LHC Run II*, **JHEP** **04** (2015) 040, [arXiv:1410.8849](https://arxiv.org/abs/1410.8849) [[hep-ph](#)].
- [87] ATLAS Collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, ATL-PHYS-PUB-2014-021, 2014. <https://cds.cern.ch/record/1966419>.
- [88] S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini, *Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO*, **Phys. Rev. Lett.** **103** (2009) 082001, [arXiv:0903.2120](https://arxiv.org/abs/0903.2120) [[hep-ph](#)].

-
- [89] ATLAS Collaboration, *Comparison of Monte Carlo generator predictions to ATLAS measurements of top pair production at 7 TeV*, ATL-PHYS-PUB-2015-002 (2015) .
<http://cdsweb.cern.ch/record/1981319>.
- [90] M. Bahr et al., *Herwig++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639–707, [arXiv:0803.0883 \[hep-ph\]](#).
- [91] ATLAS Collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 145, [arXiv:1406.3660 \[hep-ex\]](#).
- [92] T. Gleisberg et al., *Event generation with SHERPA 1.1*, *JHEP* **02** (2009) 007, [arXiv:0811.4622 \[hep-ph\]](#).
- [93] D. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152–155.
- [94] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852–867, [arXiv:0710.3820 \[hep-ph\]](#).
- [95] A. Hoecker et al., *TMVA - Toolkit for Multivariate Data Analysis*, 2007. [arXiv:physics/0703039 \[physics.data-an\]](#).
- [96] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **76** (2016) no. 12, 653, [arXiv:1608.03953 \[hep-ex\]](#).
- [97] *Cross section uncertainties*, .
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_q_SMSummary_Table1/ATLAS_q_SMSummary_Table1_201608.png.
- [98] S. Frixione, E. Laenen, P. Motylinski, B. R. Webber, and C. D. White, *Single-top hadroproduction in association with a W boson*, *JHEP* **07** (2008) 029, [arXiv:0805.3067 \[hep-ph\]](#).
- [99] CMS Collaboration, *Evidence for the Higgs boson decay to a bottom quark–antiquark pair*, *Phys. Lett.* **B780** (2018) 501–532, [arXiv:1709.07497 \[hep-ex\]](#).
- [100] ATLAS Collaboration, *Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector*, ATL-CONF-2018-036 (2018) .
<https://cds.cern.ch/record/2630338>.
- [101] ATLAS Collaboration, *Summary of ATLAS Pythia 8 tunes*, ATL-PHYS-PUB-2012-003 (2012) .
- [102] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, *Parton distributions for the LHC*, *Eur. Phys. J. C* **63** (2009) 189–285, [arXiv:0901.0002 \[hep-ph\]](#).
- [103] G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter, and F. Tramontano, *Automated One-Loop Calculations with GoSam*, *Eur. Phys. J. C* **72** (2012) 1889, [arXiv:1111.2034 \[hep-ph\]](#).
- [104] K. Hamilton, P. Nason, and G. Zanderighi, *MINLO: Multi-Scale Improved NLO*, *JHEP* **10** (2012) 155, [arXiv:1206.3572 \[hep-ph\]](#).

- [105] G. Luisoni, P. Nason, C. Oleari, and F. Tramontano, *HW[±]/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO*, *JHEP* **10** (2013) 083, [arXiv:1306.2542 \[hep-ph\]](#).
- [106] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001, [arXiv:1510.03865 \[hep-ph\]](#).
- [107] A. Denner, S. Dittmaier, S. Kallweit, and A. Muck, *Electroweak corrections to Higgs-strahlung off W/Z bosons at the Tevatron and the LHC with HAWK*, *JHEP* **03** (2012) 075, [arXiv:1112.5142 \[hep-ph\]](#).
- [108] A. Denner, S. Dittmaier, S. Kallweit, and A. Mück, *HAWK 2.0: A Monte Carlo program for Higgs production in vector-boson fusion and Higgs strahlung at hadron colliders*, *Comput. Phys. Commun.* **195** (2015) 161–171, [arXiv:1412.5390 \[hep-ph\]](#).
- [109] S. Frixione, P. Nason, and G. Ridolfi, *A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, *JHEP* **09** (2007) 126, [arXiv:0707.3088 \[hep-ph\]](#).
- [110] S. Alioli, P. Nason, C. Oleari, and E. Re, *NLO single-top production matched with shower in POWHEG: s- and t-channel contributions*, *JHEP* **09** (2009) 111, [arXiv:0907.4076 \[hep-ph\]](#). [Erratum: *JHEP* **02** (2010) 011].
- [111] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547, [arXiv:1009.2450 \[hep-ph\]](#).
- [112] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky, and W. K. Tung, *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012, [arXiv:hep-ph/0201195 \[hep-ph\]](#).
- [113] N. Kidonakis, *NNLL resummation for s-channel single top quark production*, *Phys. Rev. D* **81** (2010) 054028, [arXiv:1001.5034 \[hep-ph\]](#).
- [114] N. Kidonakis, *Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production*, *Phys. Rev. D* **83** (2011) 091503, [arXiv:1103.2792 \[hep-ph\]](#).
- [115] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W- or H-*, *Phys. Rev. D* **82** (2010) 054018, [arXiv:1005.4451 \[hep-ph\]](#).
- [116] A. Buckley, J. Butterworth, L. Lonnblad, D. Grellscheid, H. Hoeth, J. Monk, H. Schulz, and F. Siegert, *Rivet user manual*, *Comput. Phys. Commun.* **184** (2013) 2803–2819, [arXiv:1003.0694 \[hep-ph\]](#).
- [117] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) no. 4, 196, [arXiv:1512.01178 \[hep-ph\]](#).
- [118] I. W. Stewart and F. J. Tackmann, *Theory uncertainties for Higgs mass and other searches using jet bins*, *Phys. Rev. D* **85** (Feb, 2012) 034011, [arXiv:1107.2117 \[hep-ph\]](#).

-
- [119] A. Djouadi, J. Kalinowski, and M. Spira, *HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension*, *Comput. Phys. Commun.* **108** (1998) 56–74, [arXiv:hep-ph/9704448](#).
 - [120] L. Moneta et al., *The RooStats Project*, 2010. [arXiv:1009.1003](#) [[physics.data-an](#)].
 - [121] W. Verkerke and D. Kirkby, *The RooFit toolkit for data modeling*, 2003. [arXiv:physics/0306116](#) [[physics.data-an](#)].
 - [122] R. J. Barlow and C. Beeston, *Fitting using finite Monte Carlo samples*, *Comput. Phys. Commun.* **77** (1993) 219–228.
 - [123] J. R. Andersen et al., *Les Houches 2017: Physics at TeV Colliders Standard Model Working Group Report*, in *10th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2017) Les Houches, France, June 5-23, 2017*. 2018. [arXiv:1803.07977](#) [[hep-ph](#)].
<http://lss.fnal.gov/archive/2018/conf/fermilab-conf-18-122-cd-t.pdf>.
 - [124] G. Apollinari, O. Brüning, T. Nakamoto, and L. Rossi, *High Luminosity Large Hadron Collider HL-LHC*, *CERN Yellow Report* (2015) no. 5, 1–19, [arXiv:1705.08830](#) [[physics.acc-ph](#)].
 - [125] ATLAS Collaboration, *Physics at a High-Luminosity LHC with ATLAS (Update)*, ATL-PHYS-PUB-2012-004 (2012) . <https://cds.cern.ch/record/1484890>.
 - [126] ATLAS Collaboration, *Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*, CERN-LHCC-2012-022 (2012) . <https://cds.cern.ch/record/1502664>.
 - [127] ATLAS Collaboration, *Projections for measurements of Higgs boson signal strengths and coupling parameters with the ATLAS detector at a HL-LHC*, ATL-PHYS-PUB-2014-016 (2014) . <http://cds.cern.ch/record/1956710>.