

**Determination of Spin
and Parity of the Higgs boson
in the $WW^* \rightarrow e\nu\mu\nu$ decay channel
with the ATLAS detector**



Nikolaos Karastathis

DETERMINATION OF THE SPIN
AND PARITY OF THE HIGGS
BOSON IN THE $WW^* \rightarrow e\nu\mu\nu$
DECAY CHANNEL WITH THE
ATLAS DETECTOR

DISSERTATION

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on account of the decision of the graduation committee,
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by

Nikolaos Karastathis, MSc
born on October 9, 1987
in Athens, Greece

This dissertation has been approved by:

Promotor prof. dr. ing. B. van Eijk

Promotor prof. dr. G. Tsipolitis

Assistant promotor dr. P. Ferrari

Determination of the spin and parity of the Higgs boson
in the $WW^* \rightarrow e\nu\mu\nu$ decay channel with the ATLAS detector

Nikolaos Karastathis

Ph.D. thesis, University of Twente, The Netherlands

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ATLAS DETECTOR

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The cover picture illustrates a Higgs candidate event decaying into $WW^ \rightarrow e\nu\mu\nu$, as seen by the ATLAS detector.*

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ΝΙΚΟΛΑΟΥ Δ. ΚΑΡΑΣΤΑΘΗ

Διπλωματούχου Φυσικού Εφαρμογών Ε.Μ.Π.

ΕΠΙΒΛΕΠΩΝ :

Γ. ΤΣΙΠΟΛΙΤΗΣ

Καθηγητής Ε.Μ.Π.

ΑΘΗΝΑ, Φεβρουάριος 2016



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ΕΠΙΤΡΟΠΗ:**

1. Γ. Τσιπολίτης, Καθ. Ε.Μ.Π.
2. Θ. Αλεξόπουλος, Καθ. Ε.Μ.Π.
3. P. Ferrari, Ερευν. Nikhef

**ΕΠΤΑΜΕΛΗΣ ΕΞΕΤΑΣΤΙΚΗ
ΕΠΙΤΡΟΠΗ:**

1. Γ. Τσιπολίτης, Καθ. Ε.Μ.Π.
2. B. van Eijk, Καθ. Παν. Τβέντε
3. P. Ferrari, Ερευν. Nikhef
4. Π. Χριστάκογλου, Επικ. Καθ. Ε.Μ.Π.
5. Θ. Αλεξόπουλος, Καθ. Ε.Μ.Π.
6. Ε. Γαζής, Καθ. Ε.Μ.Π.
7. F. L. Linde, Καθ. Παν. Άμστερνταμ

ΑΘΗΝΑ, Φεβρουάριος 2016

To Dimitris and Giota

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Preface

Imagine putting together the pieces of a puzzle, depicting a stunning natural scenery, for almost 100 years. Then, at the end you realise that you miss the central piece that connects all the rest. You start thinking where you might have lost it, and theorise that it might be in the lost-and-found bucket; the bucket with all the pieces that belong to other puzzles that you had once put together. So you start searching and searching; and you have been searching for almost 50 years now...

This was the situation of the particle physics community before 2012. The Standard Model, the best studied quantum field theory framework that describes the particle constituents of the world that surrounds us, had been missing its central piece: the mechanism that gives all the other elementary particles their masses. This mechanism was theorised back in the 1960's to have its roots in the existence of a scalar boson: the so-called Higgs boson.

Since then countless experiments (well, buckets) have been conducted to identify this rare process in the data. However, these experiments only managed to put limits on the mass of this boson, without ever discovering it. Starting with a possible range between 10 GeV and 1 TeV, the searches were not easy to perform. One of the most stringent limits was given by the LEP collaborations, for a Higgs boson within the $114 < m_H < 158$ GeV and $m_H > 175$ GeV. Then the LHC replaced LEP. Smashing protons at an energy level unseen up to then, it provided to the general purpose detectors mounted along its ring, ATLAS and CMS, the data necessary to identify the missing piece in the bucket.

This brings us to July 2012. The ATLAS and CMS collaborations independently announced the observation of a new resonance in their searches for the Standard Model Higgs boson, both at the mass of about $m_H = 125$ GeV. *But how could you know that this is indeed the piece that you were looking for?* Simple! You have to test if it *fits* well within your puzzle. You have to study its properties: see how well it connects with the other pieces (couplings), as well as intrinsic properties as the spin and the parity quantum numbers.

The study of the spin and parity quantum numbers of the newly observed resonance is the subject of this manuscript. But let me explain its organisation and my

personal contributions on the material presented

- **Chapter 1:** briefly describes the Standard Model focusing on the Electroweak sector and how particle physics can be performed on hadron colliders. It also introduces the main production and decay modes of the Higgs boson, focusing on the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ one and explains the approach that was taken for the analysis of the Higgs boson properties;
- **Chapter 2:** introduces the machines (accelerator and detector) used to collect the data for the searches. My contribution is on developing and maintaining the framework that is responsible of controlling and monitoring the power supply of the Monitored Drift Tubes chambers of the ATLAS Muon Spectrometer. In addition I was involved in the upgrade of the ATLAS Muon Spectrometer during the Long Shutdown 1 (Appendix I). Finally, looking towards the future (Phase-II upgrades) I was responsible of developing a Geant4 simulation software (Appendix II) that studies the detector response of the micromegas detector, which is going to be placed in the New Small Wheel upgrade of the ATLAS detector;
- **Chapter 3:** introduces the definition of the physics objects (electrons, muons, jets, triggers) that are used in the subsequent analyses; my involvement was in studying the performance of the Muon Trigger;
- **Chapter 4:** describes the two different approaches followed in this thesis to model the Higgs signal either in the case of Standard Model, or other alternative scenarios; My involvement has been on the Monte Carlo studies performed with different generators on identifying their performance, as well as building the experimental models to be later tested on the data. I was responsible for the official production of the simulated signal samples used in the analysis. Moreover, I have contributed in finding a mapping between the two approaches followed by different groups within ATLAS, therefore assisting the final combination of the results. In addition, I have developed a Matrix-Element re-weighting tool that was used for the Run-I CP analysis. The tool is used to obtain from one MC sample with a specific parity new CP states with any possible parity configuration. It is now being implemented in the official ATLAS tools repository being available for the Run-II analyses to use;
- **Chapter 5:** gives an overview of the event selection for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ properties analysis. I have contributed in defining the proper selection for the Higgs candidate events in order to maximise the total signal acceptance for all spin/CP hypotheses, while keeping the background contributions under control. Furthermore, I have studied the theoretical systematic uncertainties that govern the WW background process, which is the main source of background events;
- **Chapter 6:** describes in detail the process from designing the $H \rightarrow WW^*$ analysis to target the spin of the Higgs boson, up to the final $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ spin/CP analysis result and its dominant role on the combination of all channels. This chapter illustrates my contribution on designing the analysis to be able to separate between different signal and background classes. I have optimised the chosen design to fully exploit the Machine Learning techniques for the purpose of the analysis. I defined the signal and control regions of the study. Also, I have performed background validation studies to ensure the

proper behaviour of the Machine Learning algorithm and studied the correlation among the quantities that provide information on the channel under study to make sure that the maximum information is extracted from the data and it is consistent. I have studied the impact of the systematic uncertainties on the result and helped optimize the statistical treatment of the analysis. Finally, I was responsible of running the analysis and producing the results for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis both for our separate analysis, and the combined paper.

- **Chapter 7:** describes the updated $H \rightarrow WW^*$ spin analysis, and the new parity-targeted analysis. Based on the knowledge gained from the previous publication, I have optimised the analysis for the parity studies. I have performed similar validation studies, both for the spin and parity analyses and studied in detail the background composition of the channel. Also, I have provided the estimations of the WW theory systematic uncertainties. Finally, I was responsible for running the analysis and performing the cross-checks required during the process of the independent publication, as well as the combined one.

The manuscript finishes with the summary.

CHAPTER 1

Introduction

Having its root to the greek word *physis* meaning *nature*, Physics is the fundamental branch of natural sciences. Its goal is ultimately defined as "the study and understanding of matter, energy as well as the relationship between them". These studies are performed following the so-called *scientific method* that is based on the formulation of a hypothesis. The hypothesis follows a specific model structured to explain certain observations. Based on the model, predictions are derived that lead to the need to test experimentally their validity in order to increase the confidence to the fact that the model is describing the natural world at the maximum possible detail.

Coming back to the study of matter and its interactions, the model on which the hypotheses for new observations are based is the Standard Model of elementary particles. In this chapter, a short description of this model will be presented. In addition, specific experimental information on tests that have been performed to validate this model are discussed, along with the phenomenology of predictions based on the model.

1.1 The Standard Model of Elementary Particles

The Standard Model (SM) [1–6] of elementary particle physics is the theoretical framework which describes in a unique mathematical formulation the building blocks of matter (*fermions*) and their interaction via the exchange of mediators (*gauge bosons*, Table 1.2) that define the dynamics of the system. In terms of Quantum Field Theory the particles are described as quanta of the field, while the interactions emerging through the principle of the Lagrangian invariance under local gauge transformations of a symmetry group.

The elementary particles in the SM are divided into two groups based on their

spin properties: fermions (particles with half integer spin) and bosons (particles with integer spin). Tables 1.1 and 1.2 summarise the particle content of the SM. Fermions are either leptons or quarks, divided into three families sharing their properties. Based on the properties of the symmetry group that governs each interaction, quarks take part in all interactions, leptons do not interact strongly and neutrinos interact only weakly. The complete SM is described with the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ symmetry group: 8 massless $G_\mu^{1,2,\dots,8}$ gluon fields corresponding to the generators of the $SU(3)_C$ group carry the strong force, while the photon and the $W^\pm$, Z bosons are the mixtures of gauge fields that are associated with the $SU(2)_L \otimes U(1)_Y$ that describes the electroweak interaction. The gravity is not included up to now in the SM, since, with the current understanding, its impact at the level of elementary particles is negligible.

Family	Leptons				Quarks		
	Flavour	Charge (e)	Mass (GeV)		Flavour	Charge (e)	Mass (GeV)
1 st	ν_e	0	$< 3 \cdot 10^{-9}$		u (up)	2/3	$2.3 \cdot 10^{-3}$
	e	-1	$511 \cdot 10^{-6}$		d (down)	-1/3	$4.8 \cdot 10^{-3}$
2 nd	ν_μ	0	$< 0.19 \cdot 10^{-3}$		c (charm)	2/3	1.275
	μ	-1	$113.4 \cdot 10^{-3}$		s (strange)	-1/3	0.095
3 rd	ν_τ	0	< 0.018		t (top)	2/3	173.21
	τ	-1	1.777		b (bottom)	-1/3	4.6

Table 1.1: Summary of the basic properties of the elementary fermions in the Standard Model.

Interaction	Boson	Charge (e)	Mass (GeV)
Electromagnetic	γ	0	0
Weak	$W^\pm$	± 1	80.385 ± 0.015
	Z	0	91.188 ± 0.002
Strong	g	0	0

Table 1.2: Summary of the basic properties of the elementary bosons in the Standard Model that mediate various interactions.

Having a closer look at Tables 1.2, while following the discussion, a question comes up about the properties of the bosons: "why $W^\pm$ and Z bosons are different from the photon, in the sense that they have mass, if the electro-weak sector is unified?" Which can be easily expanded to "*Since mass is a property of the matter fields, where does it come from?*"

The theoretical ground-work to answer these questions was developed by Higgs, Brout, Englert, Guralnik, Hagen and Kibble [7–10], who based on the work of Nambu and Goldstone [11–15] on the spontaneous symmetry breaking. The spontaneous symmetry breaking mechanism assumes that the total Lagrangian of a model remains invariant under the local gauge symmetry group, but the physical states do

not. In order for a system to undergo a spontaneous symmetry breaking, the Lagrangian of the system has to be invariant under a given group of transformations, but simultaneously allow for a degenerate set of minimum energy states. When selecting one of these energy states as the ground state of the system, the symmetry is spontaneously broken.

In the non-abelian case of the SM, the electroweak sector, described by the $SU(2)_L \otimes U(1)_Y$ symmetry group. When the choice of the ground state occurs, the $SU(2)_L \otimes U(1)_Y$ breaks, but the $U(1)_Q$ does not. The fact that $U(1)_Q$ stays unbroken guarantees the conservation of electric charge, which agrees with the experimental observations, while keeping the gauge boson associated with $U(1)_Q$, the photon, massless. The result of this symmetry breaking is a scalar bosonic matter field which interacts with all the known particles, with couplings proportional to mass of each particle, and three virtual bosons that under certain transformations give to the Z and $W^\pm$ bosons their mass, while keeping the photon massless. A detailed description of the formalism behind the spontaneous symmetry breaking and the Higgs mechanism can be found in most particle physics textbooks, or simply in Ref. [16].

1.2 From Theory to Experiment... and back

The success of the Standard Model is not only due to the elegant mathematical formalism in which it describes the three fundamental forces of Nature. In addition to this, the SM has been up to now successful in predicting the experimental observations that followed. These predictions depend on the parameters that are free in the model and should be fixed, or at least bounded by the experimental discoveries. The fine-structure constant, $\alpha^{-1}(M_Z^2)$, and the Fermi constant, G_F , are two of the best measured parameters of the SM [17–19]. In addition, the strong coupling constant has been determined in various experiments in e^+e^- collisions [20]. The masses of the fermions and vector bosons, as well as the weak mixing angle, θ_W from which the physical gauge bosons are created, are also parameters of the Model.

Starting by the observation of a neutral current process [21], as the one predicted by the Z boson, the c-quark and the b-quark [22] have been discovered at CERN in the 70s and 80s, along with the τ lepton and its neutrino [23]. Especially the discovery of a third generation quark provides a mechanism for CP violation through the complex phase of the Cabibbo-Kobayashi-Maskawa matrix [24,25]. Shortly after, the discovery of W and Z bosons at the CERN's $SppS$ collider followed [26].

The perturbative nature of the theoretical ground-work of the SM, allows for physics observables to be predicted and computed using perturbation theory and higher order corrections that arise from loop diagrams. One case that corresponds to this is the discovery of the t-quark in 1995 at Tevatron [27]. The mass of the t-quark was predicted from the radiative corrections to the W boson mass, as well as the $Z \rightarrow b\bar{b}$ branching ratio. The agreement between the theoretically predicted values for the parameters and the best measured experimentally ones in the electroweak sector if the SM is given by the electroweak fit. This fit is used to test the (in-)consistencies, as well as indirectly extracting constraints on the SM parameters. Figure 1.1a shows a comparison of the results of electroweak fit and the directly measured parameters of the model. The masses and widths of the vector bosons (M_Z , Γ_Z , M_W , Γ_W), the hadronic contribution to the fine-structure constant $\Delta\alpha_{had}(M_Z^2)$, the effective weak

mixing angle $\sin\theta_{eff}^2$, the mass of the Higgs boson (M_H) and the strong coupling constant α_s , but also the hadronic peak cross-section σ_{had} , partial decay widths R_i^0 and asymmetries (A_i) are all parameters of the electroweak fit [28], and can be used to extract predictions for the total electroweak sector.

As far as the Higgs boson is concerned, an upper bound on its mass at ≈ 870 GeV was set by the unitarity of the SM, especially when considering the W scattering [29]. Furthermore, the electroweak fit prediction was a Higgs mass of $M_H = 85_{-28}^{+39}$ GeV, with an upper limit of $M_H < 166$ GeV at 95% confidence level. In addition, the four experiments at the LEP collider, established a lower bound on the mass of the boson at 114.4 GeV with a confidence level of 95%, when looking at the $H \rightarrow ZZ^*$ decay channel [30]. With the same data-set, ALEPH reported an excess compatible with the production of the Standard Model Higgs boson at 115 GeV. These results are summarised in Figure 1.1b, where the confidence level of the signal plus background hypothesis over the background only hypothesis is plotted as a function of the mass of the Higgs boson. The observed (solid) and the expected limits for the background only hypothesis (dashed) lines are shown together with the one and two standard deviation uncertainties. The result from LEP is consistent with the observations from Tevatron [31]. These results combine the observations of the D0 and CDF collaborations for the Higgs searches, and quote a consistency with the background only hypothesis for masses below 110 GeV and above 145 GeV. On the other hand, the Tevatron experiments, quote an excess of about two standard deviations from the background only hypothesis in the mass range of 115 – 140 GeV. Finally, more recently a new resonance was discovered by the ATLAS [32] and CMS [33] collaborations at LHC. The resonance was found in the mass region around 125 GeV, while searching for the SM decays of the Higgs boson.

Despite the great success on the theoretical predictions followed by the experimental validation, there are still some open issues in the model. For example, one could ask the following questions

- Why there is a mass hierarchy among the fermions?
- What are the masses of the neutrinos?
- What is the nature of the invisible matter in the universe (i.e. Dark Matter)?
- Is it possible to unify the strong, weak and electromagnetic interactions?
- Can we include gravity in the SM?
- What is the reason for the matter - anti-matter asymmetry in the observed universe?

Parts of the answers to these questions may hide behind interpretations on the mechanism that generates the masses of the particles in the Standard Model framework, the Higgs mechanism. Due to the latest discovery of a resonance compatible with the SM Higgs boson, one should answer the most pressing question: *Is indeed the newly discovered resonance the scalar SM Higgs boson?* The work that is presented in this thesis is trying to answer this question, using the data collected at LHC. Therefore, it is of crucial importance to understand the way physics is performed in hardon colliders in general, but most importantly how the Higgs boson can be produced and observed.

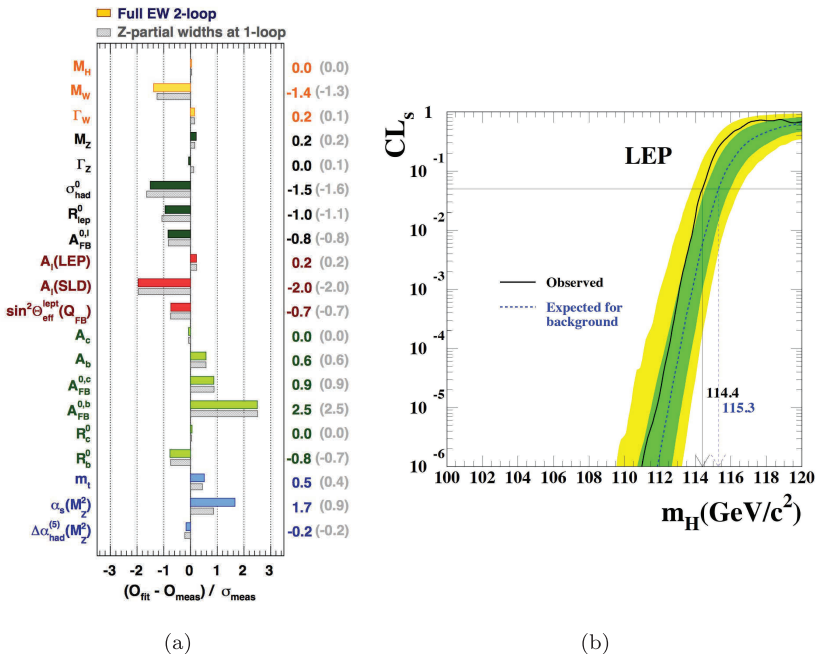


Figure 1.1: (a) The comparison of the Electroweak fit results with the direct measurements for the parameters of the fit, normalised over the total experimental uncertainty. The results of the fit are performed in two different calculations [28]. (b) The confidence level of the signal-plus-background hypothesis as a function of the mass of the Higgs boson as recorded by all LEP experiments in the $H \rightarrow ZZ^*$ decay channel [30]. The solid line represents the observed result, while the dashed the expected for the background only hypothesis. The green and yellow bands represent the one and two standard deviations uncertainty level. A small deviation from the background only hypothesis is observed at the range above 114 GeV .

1.3 Physics at Hadron Colliders

For any physics process, the production rate is given by

$$\mathcal{R} = \frac{dN}{dt} = \mathcal{L} \cdot \sigma \quad (1.1)$$

This means that the rate with which a certain process is produced depends on the product of the *luminosity*, $\mathcal{L}$, and the *cross-section* of the specific process, σ . The former is an accelerator-dependent parameter, while the latter is physics related.

The luminosity that the accelerator provides to the experiments is determined by the fine-tuning of the parameters of the machine. In detail, at a hadron collider where two beams, structured as bunches of protons, are made to collide under an angle, the luminosity is defined as

$$\mathcal{L} = \frac{N^2 \cdot n_b \cdot f \cdot \gamma}{4\pi \cdot \epsilon_n \cdot \beta^*} F, \quad (1.2)$$

where N is the number of particles in a bunch, n_b the number of bunches per beam, f is the revolution frequency, γ is the relativistic factor, ϵ_n is a factor called normalised emittance that gives the spatial spread of the beam, β^* is the beta function at the interaction point which reflects the transverse size of the beam, while F is a reduction factor due to the angle at which the two beams are colliding. All these parameters are fine-tuned to provide the maximum luminosity to an experiment. However, the maximum luminosity that is provided by the accelerator is not fully recorded by the experiments, due to dead-time issues that arise in each experiment. For example, Figure 1.2 shows the total integrated luminosity as a function of time, for the full Run-I of the ATLAS detector at the LHC machine. Different coloured contours show the luminosity that LHC provided and what was recorded by ATLAS. Furthermore, from the luminosity recorded by ATLAS, a small fraction of it is not good for physics analysis purposes, since for example, some data are of low quality due to temporary malfunctions of some ATLAS sub-system.

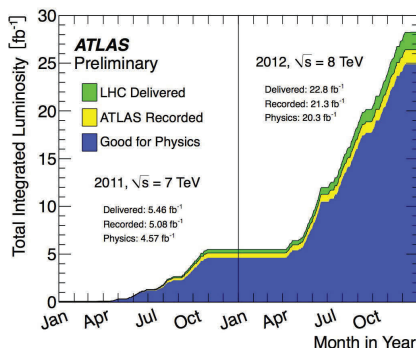


Figure 1.2: The total integrated luminosity as a function the month of the 2011 and 2012 data taking periods [34]. The different contours show the luminosity that the LHC delivered (green), the ATLAS detector recorded (yellow) and which fraction of the recorded luminosity is good for physics (blue).

On the other hand, the cross-section of a certain process is a characteristic of it. It can be linked to the probability - given a certain center-of-mass energy - that the process will take place. Contrary to lepton colliders, in a hadron collider, the beam particles are composite and not elementary. For example, the protons that are colliding in the LHC machine, can be imagined as a composite object of three bound "valence" quarks and a sea virtual quark-anti quark pairs, as well as gluons, that are continuously created and annihilated, due to quantum fluctuations. These quantum fluctuations are non-perturbative, given the low energies involved. This compositeness of the collided particle, is translated into the fact that the energy given to the particle is split amongst its constituents. Thus, in a hadron collider, the actual collisions happen between two constituents, one from each hadron, that

carry a fraction of the incoming hadron momentum, x_1 and x_2 . In such a case, the cross-section of a process H can be defined as:

$$\sigma_H(s, \mu_R, \mu_f) = \sum_{\alpha} \int_0^1 dx_1 dx_2 \cdot f_{\alpha}(x_1, \mu_f) f_{\alpha}(x_2, \mu_f) \cdot \hat{\sigma}_H(\hat{s}, \mu_R, \mu_f), \quad (1.3)$$

where α represents the different types of partons (quarks or gluons) and s is the squared center-of-mass energy provided by the collider. The function f_{α} is referred to as the parton density function (PDF), which is defined as the density of the partons in the hadron that carry x fraction of the hadron total momentum. The use of the PDFs is advantageous since it decouples the non-perturbative effects from the hard-scattering process, which is described by the term $\hat{\sigma}_H$ in Eq. 1.3. The cross-section of the hard scattering in such a scenario, is calculated in a reduced energy $\hat{s} = x_1 x_2 s$. Finally, the terms μ_f and μ_R are referred to as factorisation and renormalisation scale. The factorisation scale is introduced in order to renormalise effects as the collinear gluon splitting and the emission of soft gluons, when imposing the assumption that these quantities are finite at a given scale. In addition, the renormalisation scale is introduced to deal with divergences in the computation of the scattering amplitude of the hard process. This is due to the fact that the hard scattering cross-section, $\hat{\sigma}_H$ can be computed using perturbation theory up to a certain order.

Especially for the protons, the PDFs have been studied by deep-inelastic scattering experiments, as well as from measurements at hadron colliders [35]. Several collections of PDFs, referred to as PDF sets, exist and slightly vary due to the different approaches that have been used to extract this information from the data. For the theoretical predictions with the use of Monte Carlo simulation, a specific set is used per process. The differences between the various PDF sets for the same process are usually regarded as theoretical uncertainty when the analysis is performed. Specific details on this, will be given in the following analysis chapters.

1.4 SM Higgs Production and Decay

As far as the Higgs boson is concerned, there is a variety of production processes and decay channels that can be probed in hadron colliders, and especially at the LHC. The different mechanisms, are characterised by their cross-section at a certain energy scale. In addition, both production and decay modes have specific topological characteristics that can be exploited.

On the production side, the dominant process at the LHC is the gluon-gluon fusion (ggF), of which the diagram is shown in Figure 1.3a. In ggF, two gluons interact via a top-quark loop and produce a Higgs boson. The process is dominated by the top-quark and is an excellent production candidate to indirectly measure the Yukawa coupling to the top. The second production mode is the vector boson fusion (VBF), shown in Figure 1.3b, in which two vector bosons interact with the incoming quarks and couple directly at tree level with the Higgs boson. The topology of VBF is very distinctive, due to the presence of forward jets, but is very challenging. The third production mode, is the associated production of a Higgs and a vector boson, Figure 1.3c, referred to as VH. Similar to the VBF case, this channel exploits the quark-anti quark interaction and gives the chance to measure the direct coupling

of the Higgs to the vector bosons. Finally, the production mode with the smallest cross-section is the associated production with a pair of top quarks, shown in Figure 1.3d ($t\bar{t}H$). In this channel is important to the measurement of the Yukawa coupling to the top-quark, similarly to the ggF, but in this case without having a loop. The cross-sections for all the production modes at a center-of-mass energy at 8 TeV at the LHC are summarised in Figure 1.4a.

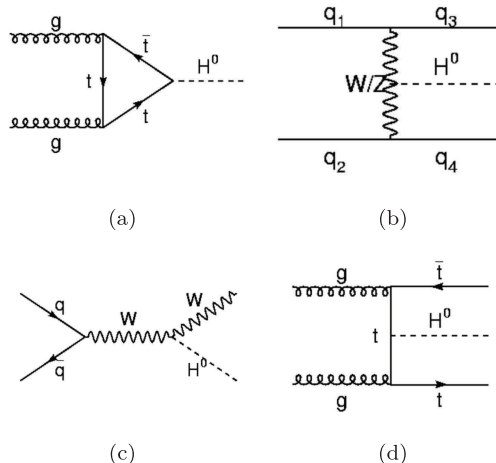


Figure 1.3: The production mechanism of the SM Higgs boson. (a) The gluon-gluon fusion (ggF), (b) the vector boson fusion (VBF), (c) the associate production (VH) and the associate top-pair production ($t\bar{t}H$).

On the decay side, the couplings of the SM Higgs boson to fermions and bosons, as well as the self couplings are shown in Figure 1.5. The Higgs boson couples directly to a fermion-anti fermion pair ($f\bar{f}$), with a coupling proportional to m_f/v , where v is the vacuum expectation value of the Higgs field ($v \approx 246$ GeV). From all the $f\bar{f}$ pairs, the $b\bar{b}$ has the largest branching ratio $\approx 57\%$, while the $\tau\tau$ is the most sensitive analysis-wise with a relative branching ratio of 6.3%. Furthermore, a direct coupling of the Higgs boson to the vector bosons is proportional to $2m_v^2/v$. The ZZ channel has a clean signature but a branching ratio of only 3%, while the WW has the highest branching ratio of 22%. Finally, the Higgs boson couples to photons via a W or top-quark loop resulting to the $\gamma\gamma$ and $Z\gamma$ final states with branching ratio of 0.2% each, while the self-coupling of the Higgs boson, with a strength proportional to $3m_H^2/v^2$ is an extremely rare channel that requires an off-shell Higgs boson. The summary of the different decay channels of the Higgs boson is shown in Figure 1.4b.

1.5 Observation of the SM Higgs-like Resonance at LHC

In July 2012, the ATLAS and CMS collaborations at LHC published their independent results on the searches for the SM Higgs boson. The ATLAS experiment, com-

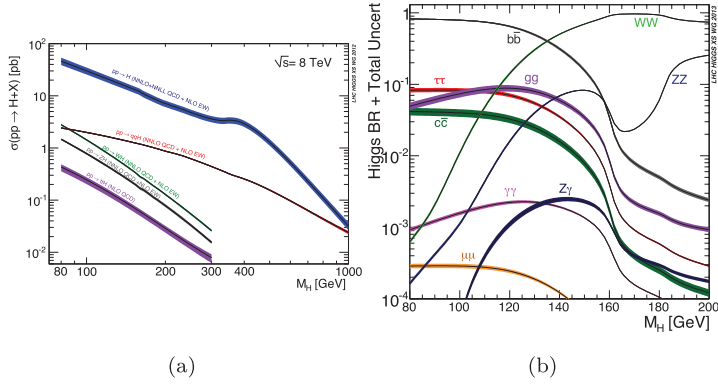


Figure 1.4: (a) Standard Model Higgs boson production cross-sections at center-of-mass energy of 8 TeV as a function of its mass [36]. (b) Standard Model Higgs boson branching ratio as a function of its mass. The width of the spline includes the total uncertainty [36].

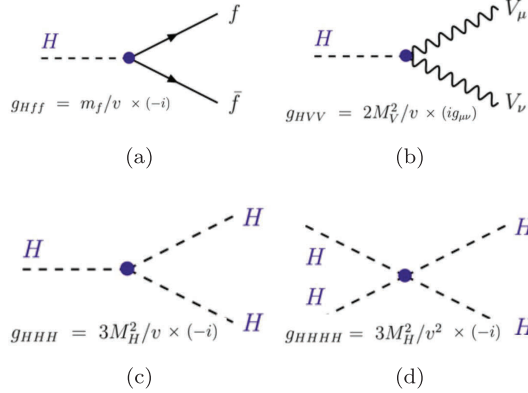


Figure 1.5: The coupling schemes of the SM Higgs boson to fermions (a) and vector bosons (b), as well as the Higgs self couplings (c,d). The coupling strengths are proportional to the mass of the coupled particle and depend on the Higgs field vacuum expectation value. The normalisation factors of the Feynman rules are also shown.

binning the $\gamma\gamma$, ZZ^* and WW^* Higgs decay channels, had announced [32] the clear evidence of the production of a neutral boson with a significance of 5.9 standard deviations. Updated searches also in the other channels had been published since then. Precise measurements of the mass in the channels with a well reconstructed mass peak ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$) have resulted in a measurement of the resonance mass of $m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})$ GeV [37], for the ATLAS collaboration. The final result for the Run-I of LHC on the mass of the Higgs boson came from the

combination of the results between ATLAS and CMS Collaborations. Figure 1.6b shows these results in terms of the log-likelihood as a function of the Higgs mass. The combined result is $m_H^{\text{ATLAS+CMS}} = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{sys}) \text{ GeV}$ [38]. The independent observation in the $H \rightarrow WW^*$ channel only came little later, with an observed excess of 6.1 standard deviations at the ATLAS combined mass [39]. Figure 1.6c shows the local- p_0 value as a function of the mass of the Higgs in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel. The observed values are drawn with a solid line, while the expected with a dashed one, under the assumption of $m_H = 125.36 \text{ GeV}$. The bands represent the one and two standard deviations uncertainty.

Up to this point, it is established that indeed a resonance exists which is compatible with the decay modes of the SM Higgs boson. The production rates of this new particle also agree with the expectations within uncertainties. However, in order to determine if the resonance is the SM Higgs boson its properties have to be studied. Separate detailed studies on the couplings to the SM particles, as well as the spin and charge-parity (CP) properties have to be performed. The latest ATLAS result for the couplings is shown in Figure 1.6d, combining the results of the Higgs boson decaying to $\gamma\gamma$, ZZ^* , WW^* , $\tau\tau$, $Vb\bar{b}$ ($V = W, Z$), $\mu\mu$, $Z\gamma$, as well as the $t\bar{t}H$ searches. The couplings to the fermions and bosons are measured in a model where only SM particles are allowed in the loop, and the result seem compatible with the SM expectation. Additional information regarding the couplings can be found in Ref. [40]. On the other hand, the full results for the spin and CP properties, that will establish the SM nature of the Higgs-like boson, and rename it to the Higgs boson, is the main focus of this thesis.

1.6 The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Decay Mode

The mass of about $m_H = 125 \text{ GeV}$ gives access to multiple fermionic and bosonic decays. The bosonic decays have a large branching ratio and relatively clean signatures in the final states compared to some of the fermionic ones. In fact, for the specific mass range, the $H \rightarrow WW^*$ decay has the second largest branching ratio (22%), after the $b\bar{b}$ mode. The decays of the W bosons can either be leptonic or hadronic. However, the leptonic decays of the W pairs have the highest experimental sensitivity in this mass range due to the clearer signature. About 7% [41] of all W pairs decay into opposite charged lepton pairs and two neutrinos. In addition, the final state has a lepton pair with large transverse momentum and large missing energy due to the presence of the two neutrinos. Thus, this signature is characteristic enough to provide a clear signal. Compared to the decay mode of $H \rightarrow ZZ^*$, where the bosons also decay leptonically, the decay into a W pair has significantly larger statistics due to the high branching fraction, but a lower signal over background ratio. Therefore, taking into account this information, despite the presence of undetected neutrinos in the final state, the statistics available in WW^* is increased by a factor of 20-30 with respect to the ZZ^* decays, making the specific channel a great channel to study the properties of the Higgs boson.

To successfully identify a $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal event and separated it from the "irreducible" WW background a further set of criteria is applied. A major characteristic of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel, which is what makes possible the observation on this channel despite the undetectable objects, is the final state topology. In detail, the two leptons of the W decays, are not expected to be back-to-back in the

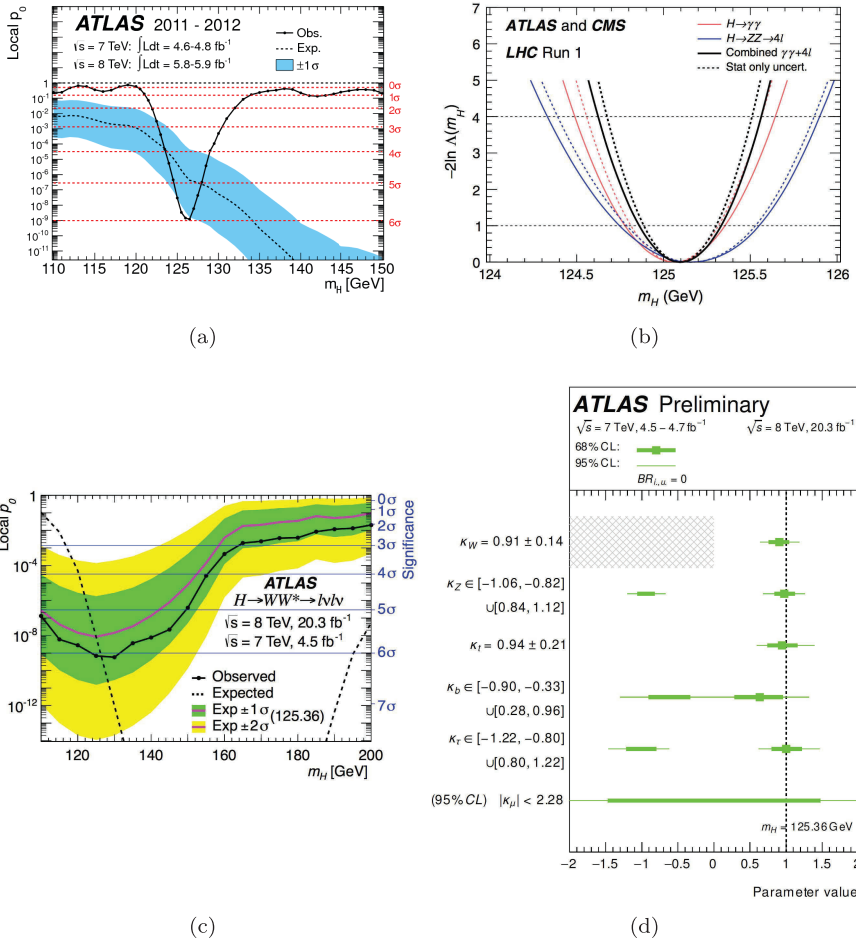


Figure 1.6: (a) The local p_0 value as a function of the Higgs mass the as observed by the ATLAS Collaboration, combining the $\gamma\gamma$, ZZ^* and WW^* decay modes [32]. The dashed horizontal lines represent the different levels of confidence. A global maximum of 5.9 standard deviations was observed. (b) Scans of the log-likelihood as a function of the Higgs boson mass for ATLAS and CMS collaboration in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ decay channels [38]. The dashed line includes only the statistical uncertainty. The combined result has a mean value of 125.09 GeV. (c) Local p_0 value as a function of the mass of the Higgs in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel [39]. The solid line represents the observed values, while the dashed are the expected ones. The expected values for a $m_H = 125.36$ GeV are shown with a solid line with the one and two standard deviations uncertainty around them. For this mass, a local excess of 6.1 standard deviations is observed. (d) Best-fit values of the couplings to fermions and bosons, in a model where only Standard Model particles are considered in the loops and excluding the existence of invisible or undetected decays of the Higgs boson [40]. The error bars represent the 68% (inner) and 95% (outer) CL intervals. All the available decay channels are used in the combination ($\gamma\gamma$, ZZ^* , WW^* , $\tau\tau$, $Vb\bar{b}$ ($V = W, Z$), $\mu\mu$, $Z\gamma$, and $\#H$).

transverse plane. In fact, the opening angle should be in the range of $10^\circ - 45^\circ$ [42,43]. This is derived from the spin correlation between the differently charged W bosons. In detail, the W bosons pairs that originate from an isotropic scalar boson should have opposite spin orientation, as shown in Figure 1.7a. In this figure the small arrows represent the direction of motion of the particles, while the large ones are the projections of their spin property. A scalar, spin-0 Higgs boson should produce W bosons with opposite orientation of spin-1 magnitude. Subsequently, due to the V-A structure of the W decay, the left-handed ℓ_L^- has to be emitted along the W^- spin. Similarly, the right-handed ℓ_R^+ has to be emitted along the W^+ spin. This configuration results to one of the charged leptons to be emitted along the momentum direction of the two W 's, and the other to be co-linearly emitted towards the opposite direction. However, if the constrain of the scalar Higgs boson is removed, then the opening angle becomes larger. This property of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay provides significant discriminating power and adds to the separation of the Higgs signal from the WW and top-quark background processes.

1.6.1 The Spin Property in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Channel

As it was mentioned, after the new resonance has been established, the next step is to measure its properties. The spin and CP properties of the SM Higgs boson are predicted to be $J^{CP} = 0^{++}$. To verify that is indeed the SM Higgs boson, alternative options on spin and CP properties have to be excluded.

The fact, that the resonance was observed in the $H \rightarrow \gamma\gamma$ channel, strongly disfavours the alternative spin-1 hypothesis. This is a result of the Landau-Yang theorem [44,45], which forbids a spin-1 resonance to decay into two photons. Another result that can be obtained by this theorem is that the eigenvalue of the charge property should be positive, $C = +1$. However, even if this hypothesis is strongly disfavoured, it should be experimentally excluded. This is driven from the fact that the observed resonance could be a non-SM Higgs boson. For example, the resonance could be decaying into two A bosons via $H \rightarrow AA \rightarrow 4\gamma$, as in the Minimal Supersymmetric Standard Model (MSSM) [46], with the two diphoton pairs to be degenerate. Therefore, the alternative hypothesis of spin-1 $^{\pm 1}$, will be tested in the $H \rightarrow WW^*$ analysis presented in this thesis.

Another spin hypothesis which has to be studied is the spin-2 case. This case is theoretically interesting as it is challenging. A massive spin-2 resonance that is minimally coupled to electromagnetism results in loss of causality, as postulated by the Velo-Zwanziger problem [47]. Such resonances present themselves with an intrinsic cut off of the order of their mass, and the most consistent effective description could be via a Kaluza Klein graviton [48]. However, using input from recent theoretical interpretations [49], a massive spin-2 graviton-like resonance should have too small couplings to the WW and ZZ compared to the couplings to $\gamma\gamma$. In addition, the couplings of this resonance to $\gamma\gamma$ should be equal to gg , and thus the widths should be $\Gamma(H \rightarrow gg) \approx 8\Gamma(H \rightarrow \gamma\gamma)$, which is not compatible with the observations so far.

In order to study the spin properties of the Higgs boson decays into pairs of Z or W bosons, the Cabibbo-Maksymowicz variables [50,51] defined in the rest frame of

¹Throughout this thesis, the notation $J^P = S^P$, e.g. $J^P = 0^+$, is adopted if a specific spin/CP configuration has to be referred to explicitly. If the CP state of the resonance is not important in the discussion at hand, the configuration will be referred to as spin-X, e.g. "spin-0".

the Higgs boson, provide crucial information about the angular distributions of the vector bosons and the final state leptons. These variables are:

- the invariant masses of the two vector bosons;
- the azimuthal Φ angle between the decay planes of the two vector bosons;
- the opening angle θ^* between the decay plane of the leading vector boson (on-shell) and the axis of the colliding partons;
- the polar angles θ_1 , θ_2 between the leading lepton, when boosted to the dilepton zero momentum frame, and the momentum vector of the dilepton system, for each dilepton system respectively;

The angular variables are shown in Figure 1.7b.

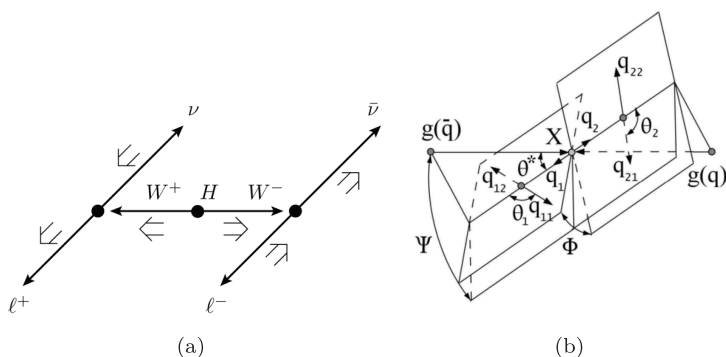


Figure 1.7: (a) The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay as depicted in the zero momentum frame of the Higgs boson. The small arrows represent the direction of motion of the particles, while the large ones are the projections of their spin. The spin correlation that arise from the helicities of the leptons due to the differently charged W bosons provide excellent discrimination power between the Higgs signal and the WW continuum. (b) A schematic drawing defining the angular Cabibbo-Maksymowicz variables: $g(q)$ refers to the incoming particles that collide to produce the bosonic resonance X . Then X decays into gauge bosons that have momentum of q_1 , q_2 in an opening angle θ^* with respect to the axis of the incoming particles. The subsequent decays into leptons with momenta q_{ij} define the decay plane of the gauge bosons, which has an opening angle Ψ with respect to the incoming particle axis. Finally, $\theta_{1,2}$ defines the angle between the momentum axis of the gauge boson and the decaying leading lepton, while Φ is the angle between the two decay planes. These variables are sensitive to the different spin and CP configurations of the primary boson, X .

In the mass range of the observed resonance, for its decay into a pair of W bosons, one of the two W 's should be off-shell. However, the invariant mass (m_2) of the off-shell gauge boson is directly proportional to the velocity $d\Gamma/dm_2 \sim \beta$, which provides an exceptionally good discriminant for the polarisation of the Higgs boson. In addition, the polarisation of the Higgs boson, depending on its CP properties should affect the Φ angle between the decay planes of the two bosons. This provides discrimination power between the CP-even and CP-odd states. In fact,

phenomenological studies have been identified the range of these variables that a SM Higgs boson should cover [42, 43]. Figure 1.8 shows an example of two of the Cabibbo-Maksymowicz variables, $\cos\theta_1$ (or $\cos\theta_2$, it is insensitive to the choice of the lepton) and Φ for a $X \rightarrow WW^*$ decay¹. with $m_X = 125.5$ GeV. The distributions are plotted for different spin hypothesis (from left to right column) : spin-0, spin-1 and spin-2. In each of the spin configuration, different CP ones are plotted; the CP-even with red circles if only minimal couplings are used, and green squares if higher dimensional operators have been taken into account, and the CP-odd corresponds to the blue triangles markers.

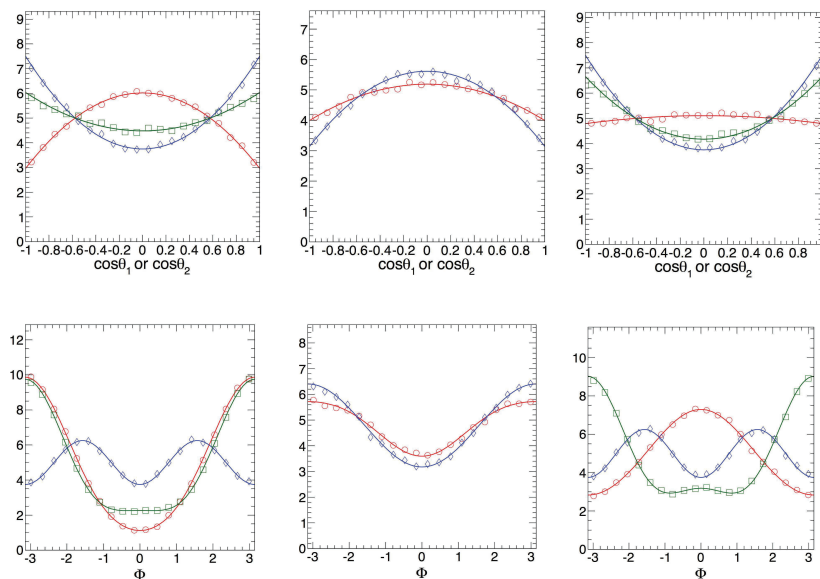


Figure 1.8: Distributions of $\cos\theta_{1,2}$ (top row) and Φ (bottom row) Cabibbo-Maksymowicz angles for the $X \rightarrow WW^*$ decay. Each column represents a different spin scenario for a spin-0 (left), a spin-1 (middle) and a spin-2 (right) resonance. For each spin hypothesis different CP configurations are shown. The red circles correspond to the CP even configuration, using only minimal couplings to the other particles, while green squares correspond to the same CP configuration but using also higher dimensional operators if available. Finally, the CP-odd state corresponds to the curve with the blue diamond marker. The plots are taken from Ref. [52]

However, these variables are cannot be observed directly in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay. The experimental observables in the final state include the four-momenta of the leptons (electrons and muons) as well as the missing transverse energy in the final state. The latter is due to the undetected neutrinos. Finally, showers of interacting hadrons, jets, can also appear in the final state. Due to the presence of the undetected

¹The notation X is adopted in order to avoid referring to non-scalar boson as "Higgs boson", since various spin hypotheses are considered.

neutrinos in the final state, the Higgs rest frame cannot be precisely reconstructed from the experimental observables. The polarisation correlations that the particles have in the rest frame of the Higgs boson, propagate to the observables in the lab frame. Figure 1.9 shows the distributions of the opening angle of the leptons in the dilepton system, $\Delta\phi_{\ell\ell}$, and the missing transverse energy arising from neutrinos, E_T^{miss} , for $X \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ for different spin and CP configurations. These plots indicate that different spin and CP configurations in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay mode can be distinguished using final state observables.

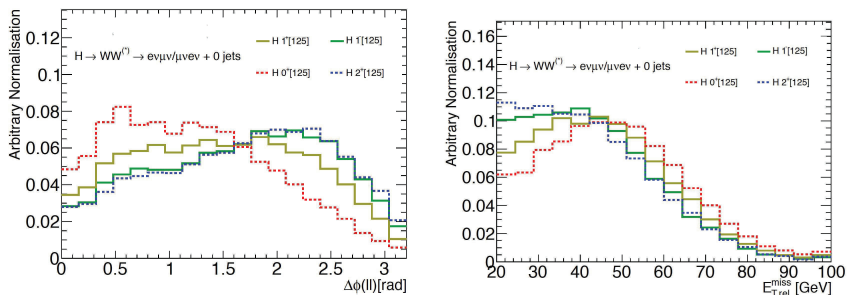


Figure 1.9: The normalised to unit area shape distributions for the $\Delta\phi_{\ell\ell}$ and $E_{T,\text{rel}}^{\text{miss}}$ variables, under the assumption of a Standard Model (red dashed), a spin-1⁺ (solid gold), a spin-1⁻ (solid green) and a spin-2⁺ (dashed blue) Higgs-boson signal.

Finally, in order to be able to analyse these observables, the physics objects on which they are dependent should be reconstructed in an experiment. In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay, this implies the need of particle detectors that identify and reconstruct tracks of charged particles (tracker), measure their energy as well as the total energy of the event (calorimeter) and are able to identify different flavours of particles (using a magnet system, muon gas chambers). In this thesis, the ATLAS detector at the LHC accelerator is used to measure the properties of the Higgs-like boson. A description of the accelerator chain and the sub-systems of the ATLAS detector will be given in Chapter 2. The details on how the different physics objects are identified and reconstructed will be discussed in Chapter 3. In addition, the specifics on the theoretical models that are tested are described in Chapter 4. Finally, the chapter with the signal selection (Chapter 5), and the analysis methods for determining the spin (Chapter 6) and the CP (Chapter 7) properties follow.

CHAPTER 2

LHC & The ATLAS Experiment

The spin and CP studies in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel that are presented in this thesis, make use of the data collected by the ATLAS detector at the LHC hadron collider. This chapter focuses on describing the characteristic properties of these two crucial components. Therefore, following the journey of the protons from their production up until their collision, the steps of the accelerator chain will be discussed. After that, the signatures arising from the collision *debris* are collected by the sub-systems of the ATLAS and are finally converted into physics objects used for further analysis. The understanding of the operation principle of the sub-detectors, working in unison to provide the physics objects, and their characteristics is of utmost importance and will be presented in detail in the following sections.

2.1 The LHC complex

The Large Hadron Collider (LHC) [53–56] is a circular proton-proton (pp) collider located at CERN in Geneva (Switzerland). The ring of $27km$ of circumference is built in the already existing LEP tunnel, as deep as 175 metres beneath the Franco-Swiss border.

The project, was approved in December 1994, aimed to extend the particle physics searches to higher energy scale and to facilitate the studies on rare, undiscovered phenomena, as well as precision measurements for the establishment of the previously observed ones. As discussed in the previous chapter, the LHC is contributing to the searches of any physics process by providing the luminosity at a certain center-of-mass energy, designed for up to $\mathcal{L} = 10^{34} cm^{-2}s^{-1}$ and $\sqrt{s} = 14$ TeV, which is the machine related parameters in the rate of a process.

At the time of writing, LHC has already completed three very successful years of operation (2010-2012) completing the first period (Run-I) of data taking, colliding protons at $\sqrt{s} = 7$ TeV and 8 TeV, as well as providing $^{82}Pb^{+} - ^{82}Pb^{+}$ heavy ion

collisions at $\sqrt{s} = 2.76$ TeV and $p - ^{82}\text{Pb}^+$ collisions at $\sqrt{s} = 5.06$ TeV. In addition, it has completed the first full Long Shutdown (LS1, 2013-2014) during which many sub-systems have been upgraded, and the start of the second data taking period (Run-II) has just started

The full accelerator chain, shown in Figure 2.1, starts from the production of protons from hydrogen atoms (H^+). These are accelerated to 50 MeV via the LINAC-2, before being injected into a series of accelerators: the Proton Synchrotron Booster (BOOSTER, up to 1.4 GeV), the Proton Synchrotron (PS, up to 25 GeV) and finally the Super Proton Synchrotron (SPS, up to 450 GeV). The final step is the injection of the beam prepared by the SPS to the LHC, where the proton beam is accelerated in both directions forming bunches of protons with a spacing of 50ns ($\sim 15\text{m}$). Finally, the accelerated beams are made to collide in a number of *interaction points* (IPs) within the accelerator ring, corresponding to the four major experiments hosted at the LHC: ATLAS, CMS, LHCb and ALICE.

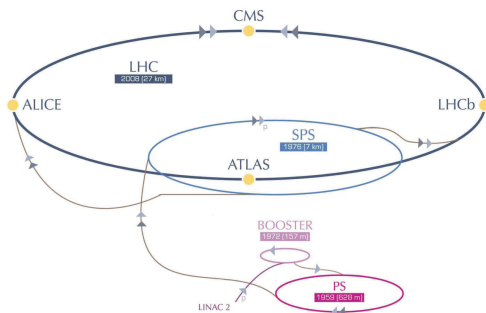


Figure 2.1: Schematic view of the accelerator chain starting from the proton production up to the collisions at the interaction points corresponding to the major LHC experiments.

Table 2.1 summarises the LHC peak performance during the Run-I in terms of the machine parameters. The data-taking period of 2010 was mainly used for the machine commissioning and testing with a center-of-mass energy of 7 TeV, delivering 48.1pb^{-1} . On the other hand, the 2011 and 2012 datasets are mainly used for physics analysis purposes with a center-of-mass energy of 7 TeV and 8 TeV and delivering 5.61fb^{-1} and 23.3fb^{-1} , respectively. The last column of the table refers to the values of settings at which the LHC was designed to operate.

2.2 The ATLAS Detector

The ATLAS (A Toroidal Lhc ApparatuS) [57] is a multi-purpose detector, specifically designed to have the largest sensitivity for a broad spectrum of physics studies that can be assessed through the LHC collisions, spanning from the Higgs discovery and precision measurements of the Standard Model, to Beyond-Standard Model and New Physics studies.

	2010	2011	2012	Nominal
Bunch Spacing [ns]	150	50	50	25
Number of bunches	368	1380	1380	2808
β^* (for ATLAS and CMS)	3.5	1.0	0.6	0.55
Max bunch intensity [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.14×10^{11}
ε_n [mm.mrad]	≈ 2.0	≈ 2.4	≈ 2.5	3.75
Peak Luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

Table 2.1: The values of the LHC machine parameters during the 2010, 2011 and 2012 data taking period. The last column represents the values for the same parameters for which the machine was designed to operate.

The detector measures 44m in length, 25m in diameter, for a total weight of 7000 tons. It is structured with cylindrical symmetry around the beam pipe, with various sub-detectors arranged in concentric layers. At the center of the cylinder, the Inner Detector (ID) [58, 59] encloses the beam pipe and is optimised to reconstruct the trajectories of charged particles. Being immersed in a magnetic field generated from the magnet system [60], the ID is capable to measure precisely the momenta of charged particles. Surrounding the ID, a calorimetry system [61, 62] consisting of an electromagnetic and a hadronic calorimeter, is designed to measure the energy of particles. Particles that interact electromagnetically or hadronically are meant to stop their trajectory within the calorimeters, by interacting with the passive material. By calculating the deposited energy, an estimate of the total energy carried by the particles can be derived. The last layer of the cylindrical ATLAS detector, the muon spectrometer [63], identifies the muons from the primary vertices of the physics processes under study. Finally, an important sub-system of the ATLAS detector is the Trigger and Data Acquisition system (TDAQ) [64], which takes upon the task on reducing the data input, rate by selecting (*triggering*) interesting events using signals from certain detector sub-systems, and re-directing the data flow towards the permanent storage facilities.

Figure 2.2 shows a cut-away view of the ATLAS detector. The geometrical dimensions of the full system, as well as the sub-systems of which the detector consists of are shown.

A common coordinate system is used throughout ATLAS, in which the interaction point (IP) is defined as its origin. The z -axis runs along the beam pipe and the transverse $x - y$ plane is perpendicular to it. Characteristic properties of the particles, as for example the the momenta which are measured in this plane are referred to as *transverse* momenta, denoted as p_T . The positive x -axis points towards the center of the LHC; the positive of the y -axis points towards the surface of the earth. The detector half at positive z -values is referred to as *Side A*, while the other half as *Side C*. Finally, due to the cylindrical symmetry of ATLAS, the transverse plane is described in $r - \phi$ coordinates, where ϕ is the azimuthal angle measured from the x -axis around the beam pipe, and r is the radial dimension measuring the distance from it. In this scheme, the polar angle θ is defined as the angle from the positive z -axis. However, most usually, the polar angle is reported in terms of *pseudorapidity* $\eta = -\ln \tan(\theta/2)$. Therefore, the distance ΔR in the $\eta - \phi$ space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

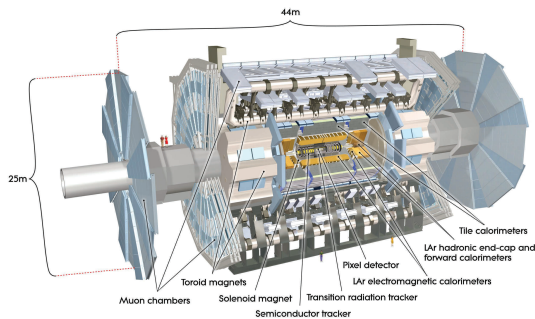


Figure 2.2: A cut-away view of the full ATLAS detector.

Due to its geometrical symmetry, the ATLAS detector can be divided into three regions. The *barrel*, which is the cylindrically symmetrical central part of the detector covering the range $|\eta| \lesssim 1.4$, and two *end-caps* (one in each side A, C) which are the circular structure that close hermetically the detector in each side of the barrel and provides a coverage in the range of $1.5 < |\eta| < 5$, with some overlap with the barrel coverage.

2.2.1 The Magnet System

The magnet system of ATLAS is a special characteristic of the detector. As shown in Figure 2.3, which only shows the magnets of the detector, it consists of four large superconducting magnets designed to provide a magnetic field mostly orthogonal to the trajectory of the particle. A Central Solenoid (CS), with a magnetic field up to $2T$ in the tracker and three air-core toroids, one in the barrel region and two in the end-caps providing an up to $4.1T$ field, are parts of the magnet system. This structure is proven advantageous in extending the coverage of the Muon Spectrometer at larger pseudorapidity values as well as having no magnetic field inside the calorimetry system in order to not degrade its performance.

The CS is $5.3m$ long with a diameter of $2.4m$, while the end-caps are $5m$ long and have an external diameter of $10.7m$ and an internal bore of $1.65m$. The end-cap toroids are rotated by 22.5° with respect to the central barrel in order to improve the overlap of the respective magnetic fields and achieve higher uniformity.

2.2.2 The Inner Detector

The Inner Detector is designed to efficiently reconstruct the trajectories of charged particles in $|\eta| < 2.5$ and for p_T from 500 MeV up to few TeV . In addition, the capability of acquiring the track impact parameters from primary and secondary vertices allows for the identification of short-lived particles.

The ID is within a cylinder of length of $7m$ with its center at the IP, having a radius of $1.15m$ and is fully contained within the magnetic field provided by the solenoid. It consists of three detector technologies: a Pixel detector, which is the innermost detector, followed by a SemiConductor Tracker (SCT) and a Transition

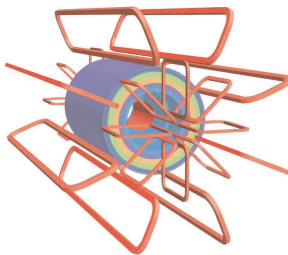


Figure 2.3: A drawing of the magnet system of the ATLAS detector. The arrangement of the solenoid and the end-cap torroids is shown.

Radiation Tracker (TRT). The first two technologies of the ID consist of radiation-hard semi-conductor based detectors that provide high precision measurements. The TRT technology is based on drift tubes and allows for a larger number of measurements to be acquired, compared to the few layers that the first two have, but with lower intrinsic resolution.

All three technologies have a barrel part, organized in concentric layers, and two end-cap counterparts, made of disks that are arranged orthogonal to the beam direction on each side of the barrel. Figure 2.4 shows a drawing of the ID in the barrel and end-cap regions. The three sub-systems that consist the Inner Detector are shown explicitly, along with their distance from the beam pipe. Combining the information from all sub-detectors of the ID, a resolution on the track momentum of $\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T (\text{GeV}) \oplus 0.1\%$ is achieved. Signals from the ID sub-systems are fed into the Trigger sub-system and used as input to on-the-fly select interesting events.

The total thickness of the ID is about $0.4 X_0$, increasing up to $1.5 X_0$ in the forward region, due to the presence of non-detecting materials (electronics, cooling systems, etc).

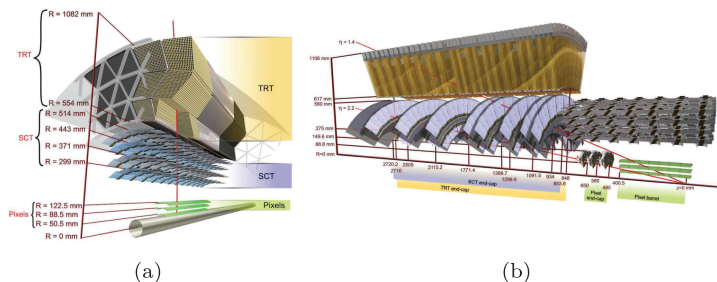


Figure 2.4: Drawing of the Inner Detector in the Barrel (a) and in the End-cap (b) regions.

- **Pixel Detector:** Based on silicon chip technology segmented in a matrix of pixels, the Pixel detector offers two dimensional spatial information. The size of each silicon pixel is of $50 \times 400 \mu\text{m}^2$ with a thickness of $250 \mu\text{m}$, with its shortest direction aligned in the direction of the bending plane of the particle, which ensures the best performance. The basic module of a Pixel sensor is a plane consisting of 144×328 pixels. In total about 1800 modules are assembled in the barrel and end-cap regions summing up to about 80 millions channels.

As mentioned, the detector has both a barrel and an end-cap part. In the central barrel region, the modules are organized in three cylinders of length of 80cm and radii of 5.05cm (called B-layer), 8.85cm (called layer 1) and 12.25cm (called layer 2). In the end-caps, the modules are organized in disks of 34cm radius and placed at $|z| = 49.5, 58.0$ and 65.0cm from the center of ATLAS.

The high granularity of the Pixel detector contributes in the reconstruction of tracks, since it provides at least three (one per layer) precise hits close to the interaction point. These hits are of utmost importance for the reconstruction of the primary vertices by measuring the impact parameter of the tracks, which are defined as the minimum distance of the track to the primary vertex. Overall, the pixel detector offers an intrinsic accuracy of $10 \mu\text{m}$ in $r - \phi$ and $115 \mu\text{m}$ in z .

- **SemiConductor Tracker:** Based on the silicon technology, the middle layer of the ID consists of four concentric layers in the barrel region, covering a range of $|\eta| < 1.4$, and of nine disks in each end-cap region, spanning $1.1 < |\eta| < 2.5$. Each layer consists of two detector modules of micro-strip detectors mounted back-to-back and placed with the micro-strips tilted by a small angle ($\sim 40\text{mrad}$), to the magnetic field (and to the beam line), in order to provide three dimensional information. The double barrel layers are mounted at radial distances of $30.0, 37.3, 44.7$ and 52.0cm . The end-cap SCT disks, consisting of modules organized radially, are mounted at z distances between $\pm 85\text{cm}$ and 272cm .

The SCT has a total number of 15392 sensors organized in 4088 modules. Each module measures $6.36 \times 6.40\text{cm}^2$ with a thickness of $350 \mu\text{m}$ and holds 780 strips with $80 \mu\text{m}$ strip pitch. This results in about 6.3 million readout channels.

The SCT is highly granular and can achieve a spatial resolution of $17 \mu\text{m}$ in the strip pitch direction and of $580 \mu\text{m}$ in the z direction. The three dimensional spatial information for (at least) four points per track over the full ID coverage helps with the track reconstruction in terms of increased impact parameter resolution, as well as the measurement of the momentum.

- **Transition Radiation Tracker:** The outermost sub-detector of the ID, the TRT, is based on the multi-wire proportional chamber technology utilizing drift (straw) tubes. This provides a relatively cheap, radiation-hard solution to extend the continuous tracking, both in barrel and end-cap regions. The barrel section is constructed out of 5×10^4 straws of 114cm length and 4mm diameter, parallel to the beam axis, from a radius 56cm , up to 107cm , thus covering a region of $|\eta| < 0.7$. In addition, each end-cap section consists of 32×10^4 straws of length of 37cm oriented in the radial direction, at z distances between $\pm 84\text{cm}$ and 271cm , covering $0.7 < |\eta| < 2.5$

- **Electromagnetic Calorimeter (ECAL):** A liquid Argon (LAr) sampling detector with accordion shaped electrodes and 1.8mm thick lead plates as absorber. The LAr has been chosen due to its linear behaviour, high ionization yield as well as its stable and radiation resistant characteristics. The shape of the accordion electrodes provides full ϕ symmetry without any azimuthal cracks. The material and thickness of the absorber has been optimized to allow for low cost while being fully efficient and providing high energy resolution. Therefore, the total thickness of the ECAL depends on η and increases from 22 to 33 radiation lengths in the barrel and from 24 to 38 radiation lengths in the end-cap, which allows for the full containment of electrons and photons with p_T up to a few TeV. The energy resolution provided by the ECAL is $\sigma_E/E = 9\%/\sqrt{E} \oplus 0.3\%$, with the energy in GeV.

The barrel part of the ECAL ($|\eta| < 1.5$) consists of two identical "half"-barrels with a small gap of few mm at $z = 0$, while each end-cap is divided into two co-axial cylinders covering the region of $1.375 < |\eta| < 3.2$. In the central region ($|\eta| < 1.8$), a pre-sample layer is present, the signals from which are used to calibrate the energy losses from electrons and photons due to their interactions with the material between the ECAL and the IP. This layer is in principle an active liquid argon layer of 1.1cm thickness in the barrel region and 0.5cm thickness in the end-cap.

The special characteristic of the ECAL is the segmentation (Figure 2.5b) of its different longitudinal layers that provides an excellent granularity allowing for precise energy and spatial resolution of different energies. The first layer is about 4 radiation lengths thick and the finely segmented readout of the absorber is in the η direction with strips of thickness $\Delta\eta = 0.003$, the aim of which is the precise measurement of the shower properties and is important for photon and electron identification. The middle layer of the ECAL contains most of the thickness of the calorimeter and is divided in squared cells in the $\eta - \phi$ plane with size $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The last layer, is coarsely segmented and the information that provides is used to estimate the energy loss beyond the ECAL.

- **Hadronic Calorimeter :** In contrast to the homogeneous ECAL, the hadronic calorimeter consists of independent sampling calorimeters, following different technologies. This comes as a result of the fact that at different η regions the energy flux and the performance requirements vary.
 1. A TILE CALORIMETER is used in the central region, covering $0 < |\eta| < 1.7$. It is structured as a cylinder of 11.4m length and inner and outer radii of 2.28m and 4.25m , respectively. It follows the sampling calorimetry technology with iron tiles as absorber and plastic scintillators as sensitive material. The Tile Calorimeter is organized in periodic towers in z and ϕ direction.
 2. A Hadronic End-Cap Calorimeter (HEC) covers the region of $1.5 < |\eta| < 3.2$, using copper plates as absorber and LAr as active material, due to the high radiation resistance of LAr.
 3. A Forward Calorimeter (FCAL) is used in the most forward region of $3.1 < |\eta| < 4.9$. The passive material of this calorimeter is tungsten rods

embedded in a matrix of copper, while again LAr is used as the active material.

The depth of the hadronic calorimeter is 7.4 interaction lengths λ . This allows a precise measurement of the missing energy, arising from undetected particles, as well a shielding for the Muon Spectrometer from the rest of the detector, allowing only for muons with at least p_T of a few GeV to reach it.

The resolution achieved is $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ for the TILE and HEC and $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$ for the FCAL.

2.2.4 The Muon Spectrometer

The outer part of the ATLAS detector consists of the Muon Spectrometer (MS), covering the region of $|\eta| < 2.7$. Its goal is to provide precise measurements of the muon momenta up to the high energy of few TeV. Figure 2.6 shows the cut-away view of the ATLAS detector where the sub-systems that constitute the Muon Spectrometer are explicitly shown. The MS can operate as a stand-alone trigger sub-system, providing in this way crucial input to the Trigger sub-system during data taking. The sub-system consists of four technologies providing precision measurements, as well as trigger capabilities. The MS is structured in three regions, covering different η ranges: a barrel ($|\eta| < 1.05$) and two end-caps ($1.05 < |\eta| < 2.7$).

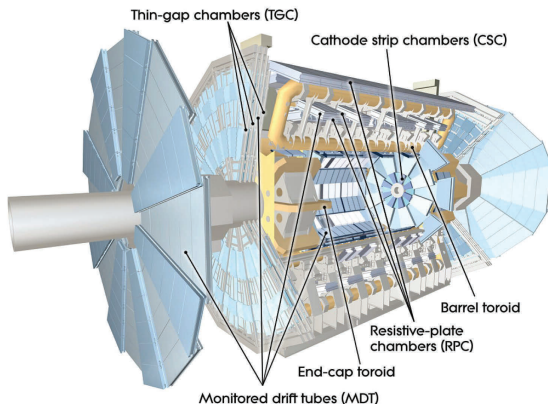


Figure 2.6: ATLAS Muon Spectrometer.
A cut-away view of the ATLAS Muon Spectrometer.

Triggering Chambers:

- **Resistive Plate Chambers (RPC):** The Resistive Plate Chambers are located in the barrel region of the MS, covering up to $|\eta| = 1.05$. The chambers consist of two parallel high resistive electrode plates that are separated by insulating spacers, creating a gap that is filled with a gas mixture of $\text{C}_2\text{H}_2\text{F}_4 : \text{iC}_4\text{H}_{10} : \text{SF}_6$ (94.7 : 5.0 : 0.3). The chambers operate with an electric field of $\sim 4.9 \text{ kV/mm}$ and the readout of the plates is done through strips

mounted at the back of the plates, orthogonal to each other, thus providing $\eta - \phi$ measurement.

The RPC's perform excellently as a fast trigger system, providing a fast momentum estimation to the hardware-based trigger within $2ns$. In addition, they provide measurements in the azimuthal coordinate ϕ with a spatial resolution of $\sim 10mm$.

- **Thin Gap Chambers (TGC):** Four layers of Thin Gap Chambers are mounted on both end-caps of the MS, covering the region $1.05 < |\eta| < 2.7$ (2.4 for triggering). They are multi-wire proportional chambers with the characteristic property that the distance between the wire and the cathode is smaller than the distance between wires. The reason for this structure is to achieve a fast charge collection time. A wire of $\sim 50\mu m$ diameter is placed between the two graphite cathode planes. The gas gap of $2.8mm$ is filled with a mixture of $CO_2 : nC_5H_{12}$ -(55 : 45). An operational voltage of $2.9kV$ is applied on the anode wires, which give the chambers signals.

The TGCs provide a timing resolution comparable to the RPCs and a spatial one varying in the range of $2 - 7mm$ for both the radial coordinate and the one orthogonal to it.

Tracking Chambers:

- **Cathode Strip Chambers (CSC):** The Cathode Strip Chambers are on the first layer of the end-caps of the MS, covering a region of $2.0 < |\eta| < 2.7$. In this region, the counting rate that can be handled by the counter-part sub-system, the Monitored Drift Tubes (MDTs), is exceeded. Thus, in the first layer of the MS, CSCs are installed, offering a safe operation with counting rates of about $1kHz/cm^2$.

The CSCs are multi-wire proportional chambers, with wires oriented in the radial direction. The chambers have two cathodes segmented in strips with orthogonal directions. CSCs are filled with a gas mixture of $Ar : CO_2$ -(80 : 20) and have an anode pitch of $2.5mm$, and a cathode strip readout strip pitch of $\sim 5.308 - 5.567mm$. By interpolating the charge between the different strips, a precise measurement of the ϕ coordinate can be achieved.

For the collection of the signal an upper limit of $40ns$ is set for the drift time. This allows for very high acquisition rates in the η range they cover. The spatial resolution achieved is $40\mu m$ in the bending plane as well as $\sim 5mm$ in the non-bending one.

- **Monitored Drift Tube Chambers (MDT):** The Monitored Drift Tube sub-system is arranged in both the barrel and end-cap regions, positioned in the ϕ direction. Each chamber is constructed by layers of aluminium drift tubes, $29.970mm$ of diameter, filled with a gas mixture of $Ar : CO_2$ -(93 : 7) at a pressure of $3bar$.

The high-energy muons ionize the gas mixture in the tube and the electrons from the ionisation are collected at the central wire, made from tungsten-rhenium (W-Re) with a diameter of $50\mu m$. The central wire is at a high voltage of $3080V$ as delivered by the Power Supply (PS) System of the MDTs. The cathode wire is held in place by a cylindrical end-plug, as shown in Figure 2.7a. The transfer of power from the PS to the chamber and of the signal from the chamber to the readout chain are placed at opposite ends of the tube.

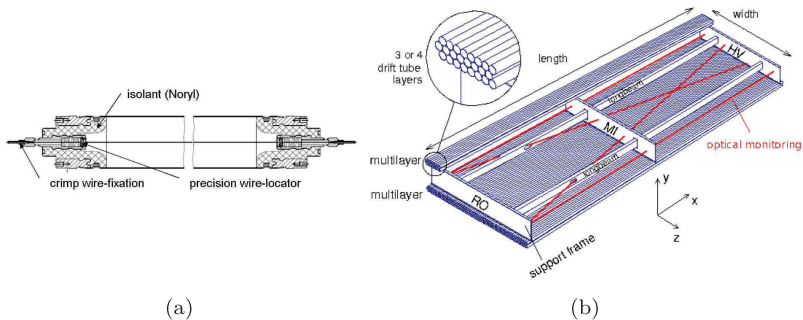


Figure 2.7: (a): Cut-away view of the inside of a Monitored Drift Tube. (b): A MDT Multi-Layer consisting of three or four rows of tubes, glued on a support frame.

Most of the MDT chambers consist of two Multi-Layers (ML), each having four rows of tubes for the innermost chambers and three rows of tubes for the rest. Depending on the relative position of the chamber in the MS, the length of the tubes may vary between 0.7 and $6.3m$, while to maintain a constant resolution, a mechanical spacer is used for fixing the position of the layers. Figure 2.7b shows a schematic of a MDT multi-layer consisting of rows of tubes glued on the supporting frame.

Due to their robustness and simple operation, the MDT chambers cover the larger area of the MS and they are used to measure the coordinate in the bending plane with a precision of $35\mu m$.

Overall, in the barrel region, the muon tracks are measured by the MDT and the RPC sub-systems with the chambers assembled in three concentric layers. The MDT provides the η coordinate and the RPC provides the ϕ coordinate together with timing information. In the end-cap region, MDT and CSC sub-systems provide the η coordinate, while the ϕ coordinate is taken from the TGC sub-system.

Apart from the combined operation mode with the rest of ATLAS, the MS is designed with the capability to measure in stand-alone mode muons with p_T from 3 GeV up to a few TeV with a momentum resolution $\sim 10\%$ at $p_T = 1$ TeV. At lower energies, the resolution improves if the MS is operated in combined mode with the ATLAS ID, reconstructing the full information from tracks in the MS and a tracks in the Inner Detector.

Most of the sub-systems of the ATLAS detector have undergone major upgrades during the LS1, to be prepared for the second period of data taking. Furthermore, plans have been made for the possible upgrades in the future. The MS is not an exception to this. In fact, in Appendix A, some additional information on the power supply system of the MDT chambers are given, as well as on the efforts of commissioning and preparation for the Run-II. Moreover, Appendix B is a look towards the future and specifically towards the Phase-II upgrades of the MS system. In this part, some simulation studies are described for a detector technology planned for future upgrades, namely the MicroMeGaS detector.

2.2.5 The Data Acquisition and Trigger System

The Trigger and Data Acquisition system (TDAQ) system is of utmost importance for a successful data taking. Its goal is to select (*trigger*) online and permanently store for later analysis only the events that contain interesting characteristics. When LHC operates at the designed luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ a bunch crossing rate of 40MHz with an average of 25 interactions per bunch crossing is achieved. However, the available resources the ATLAS detector has for offline data processing and storage are limited to $200 - 300 \text{Hz}$ which determines the average data rate of $\approx 300 \text{MB/s}$ [64].

A three-level decision chain is implemented with the aim to achieve a rejection of uninteresting events as early as possible. In each level, the rate is reduced either by fine-tuning the decisions made or applying selections on the output of the previous level. The first level (L1) is hardware-based, receiving signals from ≈ 7200 calorimeter trigger towers and $\approx 10^6$ RPC and TGC channels, as input. Each of the detectors sub-systems that contribute to the inputs of the L1 try to identify certain detector signals that could be associated to physics objects. Such objects are high- p_T electrons and photons, τ -leptons decaying into hadrons, muons and undetected ("missing") energy. Several p_T thresholds can be applied at this level. The decision of the L1 is made by exploiting the combinations of these signals (either coincidence or veto). Utilising this information, regions of interest (RoIs) are created. The maximum rate at L1 is limited to 75kHz . For the events that have been selected at L1, a read out of all the detector sub-systems is performed and the data are stored temporarily into readout buffers (ROBs). Since some of the electronics return multiplexed signals, intermediate buffers ("derandomisers") are used so that the data rate is such that the readout drivers (RODs) can handle.

The data remain at RoB until the next level, Level 2 (L2), rejects or accepts the event. The second level of the trigger system, is software-based and uses algorithms to perform reconstruction within the RoIs seeded by L1. The position, p_T , as well as the energy sums of the candidate objects, which are stored at RoBs, are accessed by L2. While the full information is available for L2, usually only a fraction is used, limited around the RoI. The L2 reduces the rate to $\approx 3 \text{kHz}$. If L2 rejects an event, then the data stored are discarded. On the other hand, if L2 accepts an event, the data stored in the RoBs are transferred by the data acquisition system to storage which is used only by the third level of the event selection (sub-farm input, SFI), the Event Filter (EF) processing units.

The EF is also a software-based selection level. Offline algorithms seeded by the information passed from the L2 run on computing farms to reconstruct the selected data, while also performing refined alignment and calibration. The final output are transferred for permanent storage. The output data rate at this level is reduced to about 200Hz with an average recording rate of $\approx 300 \text{MB/s}$.

The three levels of the Trigger and Data Acquisition system, along with the designed input and recording rates at each level are shown in Figure 2.8.

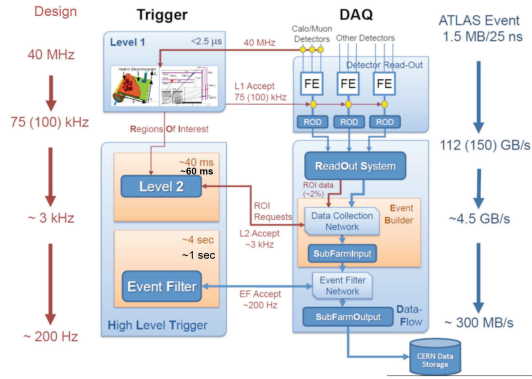


Figure 2.8: A schematic overview of the ATLAS Trigger and Data Acquisition System. The designed trigger (in red) and recording (in blue) rates are also shown for each level.

Object Reconstruction & Trigger Selection

3.1 Introduction

The particles which are produced in the proton-proton collisions in the ATLAS detector are not directly stored for further off-line analysis. On the contrary, according to their specific signatures in the sub-detectors are triggered upon and reconstructed. The procedure, referred to as *object reconstruction and identification*, allows for the definition of the final physics objects, such as leptons or jets, based on the combination of all the available information from the characteristic properties of these objects, together with the response of the detector.

For the needs of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, described in this thesis, one would need to reconstruct the leptons and neutrinos, in the form of missing transverse momentum, that appear in the final state and originate from the primary vertex. In addition, depending on the final state topology, jets might be needed. The aim of this chapter is to introduce the definition of these primary objects as well as the trigger selection for them.

3.2 Trigger Selection

All the data that are selected by the ATLAS Trigger System are stored to inclusive *streams* depending on the trigger type. There are four primary physics streams (types) : *Egamma*, *Muons*, *JetTauEtmis*, *MinBias* and several additional calibration streams. A specific *menu* defines the specific sequence (*trigger chain*, or most commonly, simply *trigger*) of reconstruction and selection steps that have to be followed to efficiently trigger upon certain signatures. The trigger chain includes two types of algorithms : Feature Extraction (FEX) ones, which are used to create an object (e.g. clusters in the calorimeter) and Hypothesis (HYPO) ones, which apply

specific selection criteria to the objects (e.g. $p_T > 20$ GeV). A trigger menu includes a number of different trigger classes:

- *Single Object Triggers*: for final states with at least one characteristic object (e.g. a single muon trigger with $p_T = 10$ GeV threshold would be a `mu10`);
- *Multiple Object Triggers*: for final states with two or more characteristic objects of the same type. For example dimuon triggers for $J/\psi \rightarrow \mu\mu$ decays (e.g. trigger requiring two muons with $p_T = 10$ GeV threshold would be a `2mu10`);
- *Combined Triggers*: for final states with two or more characteristic objects of different type (e.g. a 10 GeV muon plus 10 GeV of missing E_T would be `mu10_xe10`);
- *Topological Triggers*: for final states that require a selection based on information from more than one regions of interest.

Finally, as far as the trigger rates are concerned, they can be controlled by changing the thresholds or simply applying different sets of selection criteria. Depending on the thresholds of these selections, for a given trigger object in the menu, the triggers are denoted by the term *loose*, *medium* or *tight*, which is appended to the name of the trigger (e.g. `e10_medium`). If additional isolation selections are applied, these are denoted in the trigger name by the inclusion of an *i* (e.g. `e20i_tight`).

Prescale factors can be applied to each one of the Level-1 and High-Level Trigger chain so that only a percentage of the events passing the trigger ($1/N$) causes an event to be accepted by that trigger level. The prescale changes are applied when the luminosity drops during the fill of the LHC, to maximize the bandwidth and ensure a constant trigger rate that is useful for monitoring and calibration.

In $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, the logical **OR** of two electron triggers, two muon triggers and a dilepton trigger is used. The efficiency of the trigger is estimated from a data sample of $Z/\gamma^* \rightarrow ee, \mu\mu$ candidates.

As far as the electron triggers are concerned, they are chosen to have 24 GeV and 60 GeV p_T thresholds in the Event Filter (EF) level and satisfy the medium identification. Additional isolation criteria are applied to the electron trigger with the lowest threshold to improve its overall efficiency. The efficiency of these single-electron triggers increases with the p_T with an average of $\sim 90\%$.

For the muons the triggers have p_T thresholds of 24 GeV and 60 GeV in EF and track isolation criteria are applied. Their efficiency depends on the η range and varies from 70% for $|\eta| < 1.07$ to 90% for $|\eta| > 1.07$.

Finally, the dilepton trigger looks for an electron with $p_T > 12$ GeV and a muon with $p_T > 8$ GeV. It mainly increases the signal acceptance, allowing to lower the leading lepton p_T during the selection stage of the off-line analysis.

3.3 Tracks and Primary Vertices

Most of the physics analyses in ATLAS studying a specific decay are depending on an efficient reconstruction of the primary vertex and the tracks originating from it. This is a challenging procedure in the LHC environment. At the operating conditions of LHC, the proton-proton collisions within a bunch crossing follow a Poissonian distribution with μ as a mean value, which mainly depends on the luminosity and

the center-of-mass energy. In data delivered by LHC at the time of writing, the μ value was found to be up to 32 [65].

However, this value includes interesting collisions from the physics point of view, corresponding to the hard scattering processes, as well as non interesting ones. Due to the increased statistics, multiple hard scatterings can occur at the same bunch crossing (*in-time*). In addition, due to relatively large collection time, the calibrated sub-detectors are sensitive to interactions up to a number of preceding and immediately following bunch crossings (*out-of-time*). In the same time, soft scattering processes with minimum transverse momentum transfer (usually referred to as *Minimum Bias*), which are not interesting, can occur together with interesting ones. All of these process categories contribute to an effect named *pile-up* that makes the track and vertex reconstruction procedure (as well as other reconstruction and calibration procedures to be discussed later in this chapter) challenging.

The reconstructed tracks follow the trajectories of the charged particles and are therefore used in the definition of most physics objects. They are reconstructed in the Inner Detector using sequences of multiple pattern recognition algorithms [66]. Most analyses are using the *inside-out* track reconstruction algorithm which starts from three hits in the silicon detector and adds hits moving outwards, extrapolating to hits on the TRT sub-system.

The particles that are directly produced in the proton-proton collisions and have a mean lifetime greater than $30ps$, or the ones produced in subsequent decays or interactions with mean lifetime shorter than $30ps$, are defined as primary particles. The vertices in which these primary particles are appearing are also named primary vertices and their reconstruction is of utmost importance.

The reconstructed tracks are parametrised using a specific set of variables (d_0 , z_0 , ϕ_0 , θ , q/p) with respect to the primary vertex

- d_0 : transverse impact parameter, is the distance between the primary vertex and the closest approach of the track in the transverse plane;
- z_0 : longitudinal impact parameter; it is the z coordinate of the perigee;
- ϕ_0 : the azimuthal angle at the perigee;
- θ : the polar angle at the perigee;
- q/p : the particle charge over momentum ratio.

For the reconstruction of the primary vertices, a vertex finding algorithm [65, 67–69], seeded with the z -position at the beam-line of the reconstructed tracks is used. The algorithm performs an iterative χ^2 fit on the tracks and its result is used to apply a weight on the reconstructed tracks. This weight is used to measure the compatibility of each track with the fitted vertex. Tracks that are more than 7σ away from the vertex are discarded from the fitted vertex and are used to seed a new vertex. Each vertex is required to have at least two reconstructed tracks associated with it. The iteration is finished when no more vertices can be found. In addition, all primary vertices are constrained within the estimated *beamspot*, which is the region around the interaction point where the profiles of the two beams overlap.

For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the primary vertex of each event must have at least three reconstructed tracks with $p_T \geq 400$ MeV. In addition, it is selected as the vertex with the largest value of the $\sum p_T^2$ of all tracks associated to it.

3.4 Lepton Selection

In the scope of this thesis, leptons only include the electrons and the muons. They are the most important objects that the analyses use and therefore, special attention should be drawn to define the techniques used to reconstruct lepton candidates and then identify them as signal or background.

3.4.1 Electrons

The detector signature for an electron candidate used in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis consists of a track in the Inner Detector and an energy deposition in the Electromagnetic Calorimeter. This combined information is seeded in a three-level reconstruction algorithm, which has been developed to allow for an optimal reconstruction of the four-momentum of the electrons for the full momentum and pseudo-rapidity range, as well as for any luminosity.

The first step for the electron reconstruction is the creation of the preliminary seed clusters of the (main) electron reconstruction algorithm. These clusters are created using a *sliding-window* algorithm. In more detail, a fixed-size window of 3×5 in units of 0.025×0.025 , that correspond to the granularity of the calorimeter middle layer, slides through the $\eta \times \phi$ space of the calorimeter. In each step, if the total transverse energy within the window is a local maximum above the threshold of $E_T^{\text{thres}} = 2.5$ GeV, a cluster is constructed.

Subsequently, in the tracking volume ($|\eta| > 2.47$), the reconstructed tracks are extrapolated from their last measurement point to the middle layer of the calorimeter, where the seed-clusters were created, and are very loosely matched to them. To account for bremsstrahlung energy losses, candidate electron tracks are fitted using a Gaussian-Sum Filter (GSF) [70]. This filter takes into account the non-Gaussian noise [71] by modelling it as a weighted sum of Gaussian components and acts as a weighted sum of Kalman filters that operate in parallel [72]. Finally, an electron candidate is reconstructed if at least one track matches to the seed cluster. If more than one track matches the same seed cluster, tracks with silicon hits are preferred, and the final track is chosen to be the one with the smallest $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

The electron reconstruction finishes with the electron cluster being rebuilt using this time a 3×7 (5×5) calorimeter cells in the barrel (end-caps), for which the lateral cluster sizes were optimized to take into account the different overall energy distributions in the barrel and end-cap calorimeters. The final cluster energy is calculated by summing the estimated energy deposit in the material in front of the electromagnetic calorimeter, the measured energy deposit in the cluster, the estimated external energy deposit outside the cluster (lateral leakage) and finally the estimated energy deposit beyond the electromagnetic calorimeter (longitudinal leakage).

The four-momentum information of the central electrons is obtained from both the final cluster and the track associated to it. The energy is given by the cluster energy, while the ϕ and η directions are taken from the corresponding track parameters.

Not all reconstructed electrons are signal electrons. Hadronic jets, photon conversions, Dalitz decays or semi-leptonic heavy flavour hadron decays are all background electron candidates. To reject these background electrons as much as possible keeping the signal electrons efficiency high, ATLAS relies on discriminating variables,

which are combined into a menu of selections of varying significance and are inputs for two techniques : the selection-based and the multivariate technique.

In the selection-based menus [73], the *loose*, *medium*, *tight* and *multilepton* categories are optimized in 10 bins in $|\eta|$ and 11 bins in E_T , in order to take into account the variations of the shower shapes depending on the amount of passive material traversed before entering the electromagnetic calorimeter. The *tight* selection is a subset of *medium*, and in turn the *medium* selection is a subset of *loose*. Increasing the tightness, more variables are added in the menu and the selections are tightened on the variables already used in the looser selection.

This technique was used since the first physics run of ATLAS and kept being used for the 2011 and 2012. However, in 2012 data, the number of overlapping collisions was significantly increased during the higher instantaneous luminosity provided by the LHC. This resulted in an increase of the number of particles in an event and consequently to higher energy per event. Due to the increased energy, the shapes of the electron showers looked more background-like. To address this, additional pile-up-sensitive variables were used. Finally, a new working point was introduced, called *multilepton*, which was optimized for the low energy electrons in the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis. The increased amount of variables used spawned the idea of using a multivariate analysis (MVA) method as an electron identification technique.

For the likelihood technique the LH (stands for LikeliHood) method was used out of the different MVA techniques [74] because of its simple construction. The electron identification LH has five operating points VERY TIGHT, TIGHT, MEDIUM, LOOSE, VERY LOOSE which differ in the electron efficiency and the background rejection. Each one of the operating points is made using a different set of variables, but tighter menus are almost completely subsets of looser operating points.

Background processes for the electron identification originate from hadrons misidentified as electrons, especially at low E_T , as well as from true electrons originating from photon conversions.

The Likelihood menus improve either the signal efficiency, or the background rejection with respect to the selection-based menus. The VERY LOOSE Likelihood menu provides signal efficiencies close to 98%, compared to $\approx 96\%$ for the selection-based *Loose* menu. However, the likelihood menu has an increased by 35% background rejection. The LOOSE operating point closely resembles the *multilepton* selection-based menu in efficiency, but it further reduces the background processes by approximately 40%.

In the MEDIUM regime, both the Likelihood and the selection-based menus have the same signal efficiency. However, the Likelihood menu reduces the background contamination by half. Furthermore, at the TIGHT Likelihood menu has slightly better rejection than the selection-based menu, but roughly 5% more signal efficiency. Finally, in the VERY TIGHT Likelihood menu, the signal efficiencies are the equivalent to the selection-based one, but the background rejection is increased by half.

As far as electron identification is concerned, the 2013 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis used the selection-based identification based on the *tight* menu. This have been optimized for the 2014 analysis, where for electrons in the range of $10 < E_T < 25$ GeV the VERY TIGHT likelihood identification is used, since it reduces the backgrounds arising from light-flavour jets and photon conversion by 35%. For $E_T > 25$ GeV the selection based *medium* menu is applied, since the misidentification backgrounds are less important.

An additional requirement for the electrons is to fulfil some isolation criteria in order to further reject hadronic jets misidentified as electrons. Isolation can be track-based and/or calorimetry-based.

For the 2013 (2014)¹ analysis, as far as the track isolation is concerned, the main variable used for the isolation is the sum of the transverse momenta of all the tracks $\sum p_T$ which are consistent with the primary vertex and lay within a cone of $\Delta R < 0.04$ in the $\eta - \phi$ space around the electron direction, if the electron has a $p_T^e < 15$ GeV, or around a cone of $\Delta R < 0.03$, if $p_T^e > 15$ GeV. Only tracks that have p_T larger than a specific threshold are considered, exempting the track that had been used to build the electron object, of course. Only tracks with $\sum p_T > 0.4$ GeV (0.9 GeV) are considered. A relative upper bound of $\sum p_T/E_T^e < 0.06$ is set if $10 < p_T^e < 15$ GeV. The $\sum p_T/E_T^e$ selection increases monotonically up to 0.10. Additional requirements on the impact parameters of the tracks with respect to the primary vertex are usually applied to further reduce backgrounds misidentified as leptons. Mainly the significance of the transverse impact parameter $|d_0|/\sigma_{d_0}$ and the longitudinal impact parameter z_0 are used. The requirements for the analysis under study are $|d_0|/\sigma_{d_0} < 3.0$ and $|z_0 \sin\theta| < 0.04$ mm. The efficiency of the impact parameter and the isolation requirement for electrons varies depending on the p_T range: in the range of $10 < p_T < 15$ GeV is 68%, while for $p_T > 25$ GeV the efficiency is greater than 90%.

On the other hand, the main variable for the calorimeter-based isolation is the sum of the transverse energy of all the calorimetric cells that are within a cone of $\Delta R < 0.3$ around the electron, where the energy deposit associated to the electron is subtracted. The relative ratio that is used to set upper bound is the $\sum E_T/E_T^e$.

$$\frac{\sum E_T}{E_T^e} \begin{cases} < 0.20 & \text{if } 10 < E_T^e < 15 \text{ GeV} \\ < 0.28 & \text{if } E_T^e > 25 \text{ GeV} \end{cases}. \quad (3.1)$$

Reconstruction $\oplus$ Identification $\oplus$ Isolation Efficiency

To determine the efficiency of the reconstruction, identification and isolation selection the tag-and-probe method is applied. In the tag-and-probe method applied in the $Z \rightarrow ee$ sample for example, one electron is the "tag" that is used to select the event; this is required to be well identified and matched to a valid object. The other electron is called the "probe" and is not any more biased by any selection criteria and can be used to measure the efficiency, which is now defined as the fraction of the "probe" electrons that satisfy a selection.

To determine the electron reconstruction efficiency, $Z \rightarrow ee$ events are selected, while for the identification and isolation, additionally $J/\psi \rightarrow ee$ and $W \rightarrow e\nu_e$ events have been used to cover a large p_T spectrum. The total efficiency is the product of reconstruction, identification, trigger and isolation efficiencies. Figure 3.1 shows the electron identification efficiency for the selection-based and likelihood-based techniques in $Z \rightarrow ee$ events as a function of the E_T . The efficiency seems reasonable stable for all pile-up conditions. From the data to Monte Carlo ratios, scale factors are derived to correct for the discrepancies. These factors are found to be at the level of few % [73].

¹If a requirement is mentioned in parenthesis it represents a change between the 2013 and 2014 analyses. If no parenthesis is present the requirement was the same for both analyses.

For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the electron identification efficiency varies between 0.2% and 2.7% depending on p_T and η . The uncertainty on the isolation efficiency is 1.6% for electrons with $p_T < 15$ GeV.

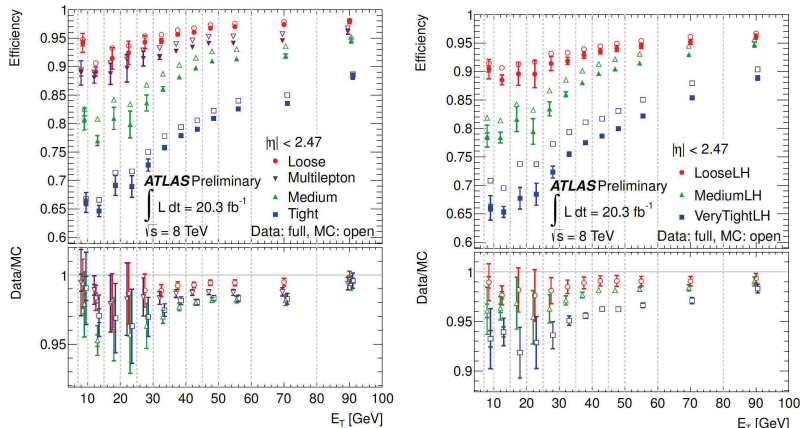


Figure 3.1: Efficiency of the electron identification in data as a function of E_T for various menus of the selection-based [73] (a) and likelihood (b) method, compared to the Monte Carlo expectation from $Z \rightarrow ee$ events. In the ratio plot, uncertainties are statistical (inner error bars) and statistical+systematic (outer error bars).

Electron Scale & Electron Scale Resolution

The energy measurement of the deposits made by electrons is also very important. The electron scale is measured in data using $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ selected events. Correction factors are derived as a function of the η of the electron. The uncertainty on the electron scale for all η bins had be found to be rather stable and well within 1%.

Fits to the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ peaks are performed to measure the data/MC agreement for the electron energy scale resolution. The relative uncertainty is better than 10% for $E_T < 50$ GeV and is increased to 40% at high energy [75].

3.4.2 Muons

For the reconstruction and identification of the muons in the $p - p$ collisions, the ATLAS detector makes use of the information from the Muon Spectrometer (MS), from the Inner Detector (ID) and, to a lesser extent, from the calorimeter.

The MS is able to detect muons up to $|\eta| = 2.7$ and to provide momentum measurement with a relative resolution better than 3% for a wide range of the p_T , while the resolution is up to 10% at $p_T \approx 1$ TeV. In addition, in the bending plane of a track within the MS sub-detectors, the single-hit resolution is about $80\mu m$ ($60\mu m$) for the MDT (CSC) sub-detectors. These tracks are reconstructed by initially acquiring all the track segments from the different layers of the muon chambers and then combining them into full MS tracks.

Due to the fact that the MS is the out-most subsystem of ATLAS, the material between the MS and the interaction point has to be taken into account during the reconstruction procedure. The amount of material is estimated to range between 100 and 190 radiation lengths (X_0), depending on the pseudorapidity range, which is mostly due to the calorimeters. The sampling liquid-argon (LAr) calorimeter is surrounded by the hadronic calorimeters based on iron and scintillator tiles. The coverage for the LAr is $|\eta| < 3.2$ while for the hadronic tiles cover a range of $|\eta| < 1.5$.

On the other hand, the ID provides independent measurement of the muon track, close to the interaction point. The Silicon Pixel, SCT and TRT detectors provide high-resolution coordinate measurements for the track reconstruction inside the axial magnetic field of $2T$. Usually, a track in the barrel region has 3 pixel hits, 8 SCT hits and about 30 TRT hits.

For the identification of the muons, four sets of criteria have been decided which depend on the reconstruction selection. These sets are usually referred as *types* of muons that belong in these sets. Out of these four types of muons, the one that is used for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis combines an independently reconstructed track in the MS, with an also independently reconstructed track in the ID. Due to this combination, this type of muons is referred to as *combined* (CB). For completeness, the other types of muons that are used in various analyses, some of which are shown in Figure 3.2 are the *Stand-Alone* (SA) muons, which are reconstructed with information taken from the MS only, the *Segment-tagged* (ST), for which segments of tracks in the MS are extrapolated to tracks in the ID and the *Calorimeter-tagged* (CaloTag), for which a track in the ID is matched to a deposit of energy in the calorimeter.

The reconstruction of the muon tracks in the MS, and consequently the CB type of muons, is mainly affected by the coverage in acceptance that the system provides. The losses in acceptance come mainly from the area of $\eta \approx 0$ where the MS is only partially equipped with chambers because of the limited space that there is, which is occupied by ID services and calorimeters. Another region that contributes to the acceptance losses is the region ($1.1 < \eta < 1.3$) between the barrel and the positive η end-cap, where there are regions in ϕ with only one layer of chambers traversed by muons in the MS, since some of the chambers were not yet installed during data taking (see Appendix A).

For the reconstruction of muons using MS information, two independent reconstruction algorithms are used implementing two different strategies [76] (name *Chains*). *Chain 1* is used for the ID-MS combination. This algorithm performs a statistical combination of the track parameters coming from the ID muon tracks, making use of the corresponding covariance matrices. *Chain 2* performs a global refit of the muon track, which makes use of the hits present in both the ID and the MS. A new algorithm, called *Chain 3* has been developed, unifying the best characteristics of *Chain 1* and *Chain 2* and was running in parallel for the 2012 data-taking. However, only the first two packages were used for the ATLAS publications. For the future data-taking period, it has been decided that the third chain will be the only one being used.

In order for an ID track to be used in the CB muon type, it should have at least one hit at the Pixel detector and at least 5 SCT hits. In addition, it should be traversed at most have 2 active Pixel or SCT sensors without hits, and finally, in the region of the full TRT acceptance ($0.1 < |\eta| < 1.9$) the track should have at least 9 TRT hits. If a track traverses a sensor already known for being inefficient, the number of

required hits for the first two requirements is decreased by one. However, all these requirements are dropped in the high- η ($|\eta| > 2.5$) region.

The muon isolation definition is similar to the one of the electrons. For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the combined muons have to satisfy both track and calorimeter based isolation criteria. In detail, for the track-based isolation the lower threshold on $\sum p_T$ is at 1 GeV. Selected muons must be in a cone of $\Delta R < 0.4$ if the $p_T^\mu < 15$ GeV, while the cone radius is less at $\Delta R < 0.3$ when $p_T^\mu > 15$ GeV. The relative ratio is defined as

$$\frac{\sum p_T}{p_T^\mu} \begin{cases} < 0.06 & \text{if } 10 < p_T^\mu < 15 \text{ GeV} \\ < 0.12 & \text{if } p_T^\mu > 25 \text{ GeV} \end{cases}. \quad (3.2)$$

In addition, the requirements on the track parameters are relatively similar to the electrons with $|d_0|/\sigma_{d_0} < 3.0$ and $|z_0 \sin\theta| < 1.0$ mm.

As far as the calorimeter-based isolation is concerned, the muon itself, as well as the calorimeter cells within $\Delta R < 0.05$ around it are excluded from the sum $\sum E_T$, while an additional correction on the number of primary vertices is applied. Finally, the relative calorimetric upper bound $\sum E_T/p_T^\mu$ is set at

$$\frac{\sum E_T}{p_T^\mu} \begin{cases} < 0.06 & \text{if } 10 < p_T^\mu < 15 \text{ GeV} \\ < 0.10 & \text{if } p_T^\mu > 25 \text{ GeV} \end{cases}. \quad (3.3)$$

Muon Reconstruction $\oplus$ Identification $\oplus$ Isolation Efficiency

The measurement of the efficiency of the muon reconstruction, identification and isolation efficiency is performed using the tag-and-probe method on $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ samples [77]. In addition, isolation requirements on the muon are used as a tool to reject muons from light-hadron decays. In principle, there is no contamination from fake muons, and the larger impact comes from the non-prompt muons. These cases are treated using the muon isolation requirements.

Figure 3.2a, shows the muon reconstruction efficiency for multiple types of muons as a function of η in a $Z \rightarrow \mu\mu$ data sample compared to the Monte Carlo simulation. The selected events have $p_T > 10$ GeV (for CaloTag only $|\eta| < 0.1$ is considered). The error bars on the efficiencies include statistical uncertainties, while the ones in the ratio plot include both statistical and systematic uncertainties. If more than one type of muons is considered, the results shows an almost uniform efficiency of 99% for the full η range. In addition, Figure 3.2b shows the muon reconstruction efficiency for CB muons as a function of the muon p_T in the range of $0.1 < |\eta| < 2.5$. The plot contains both $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ samples and clearly shows the gain at the low- p_T region with the inclusion of the J/ψ decays. Error bars include statistical uncertainty of the Z decays and the fit model uncertainties from the J/ψ decays. In the ratio plot below, the comparison between the measured and predicted efficiency is shown. Green shaded areas correspond to the statistical uncertainties, while the orange ones also include the systematic uncertainties. Finally, for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the uncertainty on the isolation efficiency is 2.7% for muons with $p_T < 15$ GeV.

Muon Momentum Scale & Resolution

The large J/ψ , Υ and $Z \rightarrow \mu\mu$ samples collected by ATLAS are all used to study the momentum scale and resolution by comparing Monte Carlo simulation with selected events in the data. While the simulation includes the best knowledge of the full

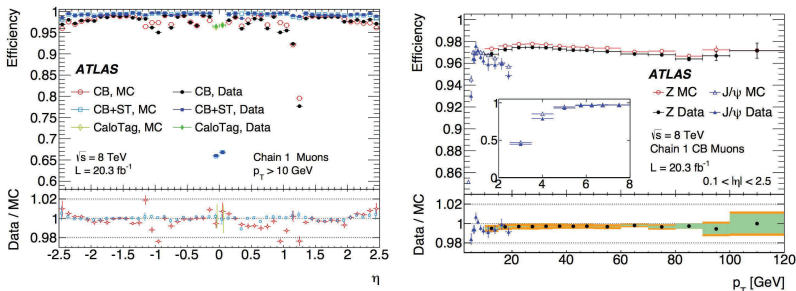


Figure 3.2: (a) The muon reconstruction efficiency for various types of Muons (CB: Combined, ST: Stand-alone; CaloTag: Calorimeter Tagged Muons) as a function of η in the $Z \rightarrow \mu\mu$ data sample compared to the simulation [77]. Error bars on the efficiency plot include statistical uncertainties, while on the ratio plot include both statistical and systematic ones. (b) The muon reconstruction efficiency for CB muons versus p_T for the $Z \rightarrow \mu\mu$ and the $J/\psi \rightarrow \mu\mu$ sample in the range of $0.1 < |\eta| < 2.5$. Error bars include statistical uncertainty of the Z decays and the fit model uncertainties from the J/ψ decays. The ratio shows the observed versus the expected in MC efficiency. The green shaded areas cover statistical uncertainties, while the yellow ones cover systematic uncertainties.

ATLAS detector, additional corrections to the MC are needed to fully reproduce the muon momentum resolution and scale that appears in the data. Template fits on the dimuon mass distribution are performed to extract the correction factors. The corrections are mainly due to the amount of material a muon has to transverse, the spatial resolution of the track as well as the relative alignment between the MS and ID, since the combined muons combine the independent information of the two sub-systems.

Figure 3.3a shows the dimuon invariant mass distribution in data and MC, before and after these corrections have been applied, for the $Z \rightarrow \mu\mu$ sample. The band in the data/MC ratio represent the effect of the systematic uncertainties on the momentum scale corrections. The corrections are at the level of few %. In addition, Figure 3.3b, shows the dimuon mass resolution for combined muons versus the leading muon η for the same sample. In the ratio plot, the error bands represent the statistical uncertainty, as well as the systematic uncertainty on the fit added in quadrature, while the band represents the total systematic uncertainty on the correction. The corrected MC distributions reproduce the behaviour that is present in the data with a relative $\sigma(m_{\mu\mu})/m_{\mu\mu}$ ranging from $\sim 1.7\%$ in the central region to $\sim 4\%$ for the low- p_T region.

3.5 Jets Selection

Energetic partons generated in the detector undergo the process of hadronisation and generate a collimated "spray" of hadrons, which is called *jet*. In Quantum Chromodynamics jets are products of the fragmentation of quarks and of gluons. The jet

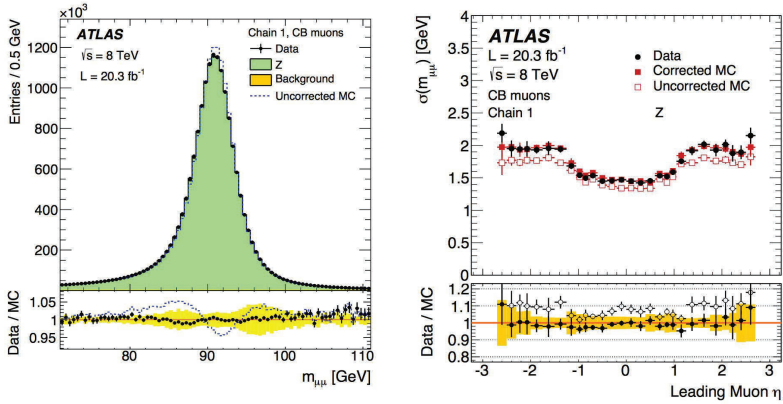


Figure 3.3: (a) The dimuon invariant mass distribution in the data and the corrected and uncorrected Monte Carlo in $Z \rightarrow \mu\mu$ events [77]. The band on the ratio plot represents the effect of the systematic uncertainties on the momentum scale corrections. (b) The dimuon mass resolution as a function of the leading muon η for the $Z \rightarrow \mu\mu$ sample [77]. The error bars on the ratio plot include the statistical uncertainty and the uncertainty on the fit added in quadrature. The error band represents the total systematic uncertainty on the correction.

of particles has null colour charge and in approximation its direction is the same to the original parton. Jets in ATLAS are reconstructed in a way that their overall properties (energy, momentum, etc) reflect as precisely as possible the short distance dynamics of the collision in which they are produced.

The jet reconstruction processes data at a very early stage during the data collection, namely at the Level-1 Trigger System and is refined by combining information from various sub-systems at the High Level Trigger. Jets are reconstructed with the anti- k_T algorithm [78] using two settings for the distance parameter at 0.4 and 0.6. Different types of jets can be defined based on the inputs of the reconstruction algorithm, such as *truth jets*, where the inputs are stable particles in simulated events. In addition, *track jets* are reconstructed with reconstructed tracks in the Inner Detector as inputs for the clustering algorithm. Finally, *calorimeter jets* where the input are the energy deposits in the calorimetry system.

The energy deposits that are used for the calorimeter jets are combined in clusters which are built from topologically connected cells of the calorimeter that give an output signal which is higher than a preset noise level [79,80]. These clusters are referred to as *topo-clusters*. The topo-clusters are reconstructed in the EM scale [81,82], which precisely measures the deposited energy by the particle interactions in the electromagnetic calorimeter. A second topo-cluster collection identifies the topological clusters as either electromagnetic, or hadronic depending on the energy density and the longitudinal shower depth. It is based on the local cell signal weighting (LCW) method, which provides an improved resolution compared to the EM scale, mainly

due to the smaller fluctuations arising from the non-compensating nature of the ATLAS calorimeter. Therefore, the aim of the jet calibration procedure is to restore the jet energy scale of the reconstructed jets in data to that reconstructed from stable simulated particles.

1. Correction due to pile-up: The jets that are formed based on topo-clusters either at the EM or the LCW scale have to be calibrated to account for the energy offset caused by the in/out-of-time pile-up effects. The corrections are based on the number of primary vertices N_{PV} in MC simulated events, which gives an indication for the in-time pile-up, as well as the expected average number of interactions μ^1 , that provides information for the out-of-time pile-up. The process for the calibration is to calculate the total transverse momentum which had been generated by pile-up in a jet in a simulated sample, and subtract this offset ($\mathcal{O}$) from the p_T of the reconstructed jet at any scale. The offset for a reference pile-up conditions is calculated to be $\mathcal{O}(N_{PV} = N_{ref}, \mu = \mu_{ref}) = 0$. However since the energy scattered within a jet cone by pile-up, as well as the modification on the signal both determine the size of the offset, a dependence on the relative difference from the reference point is expected. Thus the total offset can be calculated as

$$\mathcal{O}(N_{PV}, \mu, \eta_{det}) = \alpha(\eta_{det}) \cdot (N_{PV} - N_{PV}^{ref}) + \beta(\eta_{det}) \cdot (\mu - \mu_{ref}), \quad (3.4)$$

where $\alpha = \partial p_T^{\text{jet}} / \partial N_{PV}$ and $\beta = \partial p_T^{\text{jet}} / \partial \mu$ are the coefficients for the in-time and out-of-time pile-up. These can be taken uncorrelated, since they manifest in different calorimeter regions. The final corrected p_T is given as $p_{T,X}^{\text{corr}} = p_{T,X}^{\text{jet}} - \mathcal{O}^X(N_{PV}, \mu, \eta_{det})$, where X denotes the selection of the scale (either EM or LCW).

2. Correction due to jet origin: The jets are corrected to point back to the primary vertex instead of the interaction point.
3. Jet calibration based on simulations: Correction factors for the jet energy are derived from a comparison of the reconstructed jets in the data to the simulated ones and are applied on topo-clusters made at EM or LCW scale [85]. This results in jets calibrated with two schemes: EM+JES and LCW+JES. These factors are derived for isolated jets in an inclusive simulated sample and are applied as a function of the p_T the η of the jet [86].
4. Residual in situ corrections: The final correction factor which is applied to the data represents the residual effects that are not present in the simulation. The correction is derived using *in situ* techniques which exploit the p_T balance between the jet and a well-measured object. One technique applied is the *η -intercalibration*, in which a forward jet is calibrated against a more precisely measured central jet. On the other hand, a central jet can be calibrated *in situ* using $Z + \text{jets}$, $\gamma + \text{jets}$ and multi-jet events for the p_T balance.

For the scope of the analyses presented in this thesis, the jet calibration scheme was changed between the two publications. The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis for the

¹ $\mu = \frac{L \times \sigma_{\text{inel}}}{N_{\text{bunch}} \times f_{\text{LHC}}}$, where L is the average luminosity over a period Δt , σ_{inel} is the total inelastic $p-p$ cross-section [83], while N_{bunch} and f_{LHC} [84] are the number of bunches and the revolution frequency of LHC.

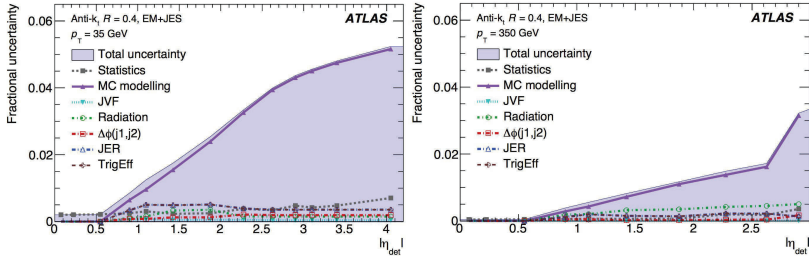


Figure 3.4: Summary of the intercalibration uncertainties as a function of the jet $|\eta|$ range in the detector for a low- p_T (a) and a medium- p_T (b) jet reconstructed with the anti- k_T algorithm with a distance parameter of $R = 0.4$ [87]. The individual components are added in quadrature with the dominant component being the Monte Carlo modelling uncertainty.

2013 Moriond results used the EM+JES scheme. However, in order to achieve a consistency between the tagging jets and the jets that were used in the definition of the missing transverse energy, in the updated 2014 analysis the jet collection was changed to LCW+JES. The jets used are also reconstructed with the anti- k_T algorithm, using a radius of $R = 0.4$ and the inputs to the clustering sequential algorithm are three-dimensional clusters of energy deposited in the calorimeter.

Jet Energy Scale & Jet Energy Resolution Uncertainties

The uncertainty on the jet energy scale (JES) is derived by a combination of test beam, simulation and *in situ* measurements, as described in full detail in [87]. The total uncertainty includes the

- modelling and statistical component on the η -intercalibration procedure. Figure 3.4 shows the summary of uncertainties on the intercalibration as a function of the jet η_{det} ;
- behaviour of high- p_T jets ($p_T > 2$ TeV) component, for which the statistics are limited;
- the non-closure uncertainties of the Monte Carlo;
- uncertainty component on the calorimetric response and on the calibration of soft jets (light quarks and gluons);
- the b-jet energy scale uncertainty component [88];
- the uncertainty component on the modelling of the in-time and out-of-time pile-up;
- the uncertainties that arise from the *in situ* jet energy corrections.

For the jets that are used in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the jet energy scale uncertainty ranges from 1 – 7% depending on p_T and η .

The uncertainty on the jet energy resolution (JER) varies from 5% to 20% depending on p_T and η , while the relative uncertainty on the resolution which is derived from *in situ* measurements [89] varies from 2% to 40%. Both the 20% of the jet energy resolution and the 40% of its relative uncertainty occur only at the p_T threshold

of the jet selection.

Jet Reconstruction Efficiency

The reconstruction efficiency for jets can be derived from a tag-and-probe method using tagged jets in data and the nominal inclusive jet in a Monte Carlo simulated sample. The efficiency has been found to be well described by the Monte Carlo, and thus, a systematic uncertainty of 2% for jet with p_T smaller than 30 GeV is applied, while for higher p_T the systematic uncertainty is negligible.

Jet Cleaning & Vertex Fraction

Jets reconstructed in the detector are not only coming from the hard scatter interaction in the $p-p$ collisions. The main background processes may include calorimetric noise, background due to beam-gas interactions and cosmic ray contamination of showers. Several quality criteria are applied and are described in detail in [85]. These criteria mainly consist of energy thresholds on the electromagnetic and hadronic calorimeters as well as the shape of electrical signals. This selection of quality jets plays also an important role in the calculation of the missing transverse momentum, where the presence of *fake* jets contribute in the p_T imbalance.

In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, an additional requirement on the Jet Vertex Fraction (JVF) [90] is applied in order to select only high quality jets. The JVF is defined as the sum of the transverse momenta of all tracks arising from the primary vertex and are matched to a jet, divided by the total jet-matched track p_T from all the vertices. This requirement is set to reduce the contributions of background fake jets arising from pile-up interactions. In the analyses presented in this thesis the requirement of JVF is $|JVF| < 0.5$ and is applied for jets with $p_T < 50$ GeV. In addition, since it requires track-matched jets, the selection is restricted in jets that are in the range of $|\eta| < 2.4$, where the Inner Detector coverage lays.

Figure 3.5 [91] shows the performance of the JVF. This was studied on $Z \rightarrow \mu\mu$ samples selected in data and Monte Carlo simulated events. The samples that are compared are the $Z \rightarrow \mu\mu + 1\text{jet}$ against all $Z \rightarrow \mu\mu$ events and are plotted as a function of the number of primary vertices.

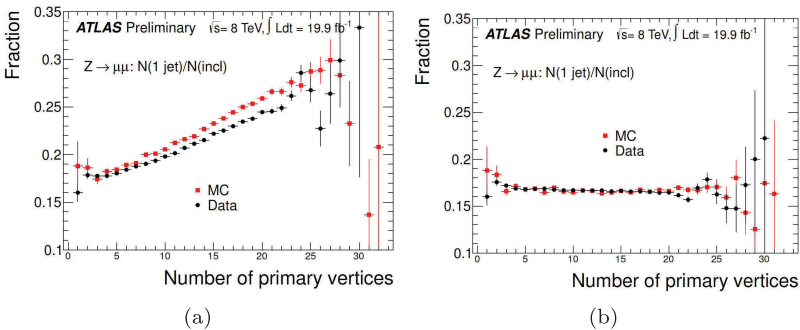


Figure 3.5: The performance of the JVF [91]. (a) has no requirement on JVF set, while (b) has an additional $|JVF| < 0.5$ requirement. The plotted uncertainties are statistical.

3.5.1 b -tagged Jets

Jets consisting of b -quark hadrons have the property of increased flight path within the detector, due to the long life-time of the b -quark. This characteristic is used to discriminate and tag jets resulting from b -quark fragmentation (*b-tagging*). This b -tagging is of utmost importance for signal final states that include b -quark particles and jets. However, in the analyses described in this thesis, the b -tagging is used as a veto, removing b -tagged jet events in order to reduce the backgrounds containing t -quarks in the topology of one or more jets in the final state.

Several algorithms are developed to identify b -jets (MV1, JETFITTERCOMBNN, JETFITTERCOMBNNc, IPD3+SV1, SV0, etc) [92–97]. These algorithms use a variety of variables to discriminate between b -hadron and light jet decays. The most discriminating variables or outputs from other algorithms can be combined in a neural network, which has as an output a weight probability density evaluating separately b , c and light-flavour jets. This algorithm is named MV1, and is trained with b -jets as signal and light-flavour jets as background and thus, it computes a tag weight for all jets.

The performance of a b -tagging algorithm, here MV1, is defined as its capability to identify jets due to real b -quark hadronisation, with respect to the probability of erroneous tagging a jet originating from a c -quark (c -tag efficiency) or a light flavour parton (u , d , s or gluon; mis-tag rate) as b -jet. Figure 3.6a shows the light-flavour rejection (and Figure 3.6b specifically for c -jets), which is defined as the inverse of the mis-tag rate, versus the b -jet efficiency of some of the b -tagging algorithms in ATLAS, for jets with $p_T > 15$ GeV and $|\eta| < 2.5$. The MV1 tagging algorithm has the best performance on rejecting light quark jets and thus, has been selected for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis.

Specific selections made on the MV1 weighted output probability, and thus on different b -tagging efficiencies and mis-tag rates, define the working points of the algorithm. For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis the operating point with 85% b -tag efficiency was selected. To evaluate the b -tag efficiency, a sample of dileptonic $t\bar{t}$ decays is used [90].

For the uncertainties that are related to the b -jet identification the eigenvector method [98] is used, since the sources can be decomposed on six uncorrelated components, number which also defines the number of p_T bins that are used in the calibration. These uncertainties vary from $< 1\%$ to 7.8% . In addition, the uncertainty on the mis-tag rate for a light-quark jet depends on the p_T and η of the jet and varies from 9% to 19% . Finally, the uncertainty on the misidentification of c -jets as b -jets depends on p_T and varies from 6% to 14% .

3.6 Missing Transverse Momentum Selection

Due to momentum conservation, all detected events have to be energy-balanced. This balancing happens in the transverse plane and not along the beam direction, since the component along the beam axis of the center-of-mass frame of the hard interaction is unknown. Electroweak interactions in the Standard Model are accompanied by neutrinos that escape undetected. In addition, processes involving particles predicted in exotic and super-symmetric scenarios are not detected either. These kind of events appear with a large amount of momentum imbalance in the transverse

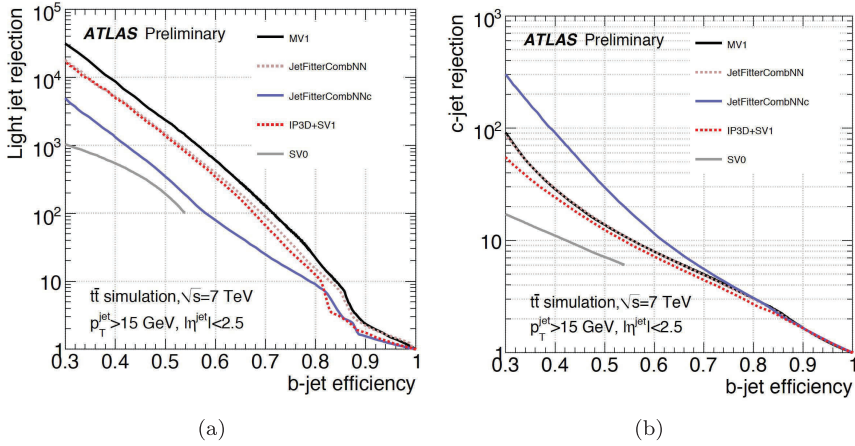


Figure 3.6: The performance of light jet rejection (a) and c -jet rejection (b) versus b -jet efficiency for various b -tagging algorithms [97].

plane. The term missing transverse energy (E_T^{miss}) is used to quantify this amount. The vector of this imbalance in the transverse plane is given by the negative vector sum of the momenta of all objects selected, according to the ATLAS identification algorithms, and of the remaining "soft" objects, that have low p_T values. The precise reconstruction and calibration of the E_T^{miss} is essential for the physics at LHC and especially for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ searches. The calculation therefore is

$$\mathbf{E}_T^{\text{miss}} = - \left(\sum_{\text{select}} \mathbf{p}_T + \sum_{\text{soft}} \mathbf{p}_T \right). \quad (3.5)$$

For the reconstruction of the E_T^{miss} [99,100], in the scope of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, various methods have been implemented and depend on the choice of selected objects and the reconstruction of soft objects.

1. Calorimeter-based E_T^{miss} :

For this definition, E_T^{miss} is reconstructed from energy deposits in the Calorimeter and from muons reconstructed in the Muon Spectrometer. Track information is added to recover the contribution from low- p_T particles which have not been detected in the Muon Spectrometer. Additionally, muons reconstructed in the Inner Detector are used to recover for the regions that are not covered by the Muon Spectrometer. As far as the information from the calorimeter is concerned, to ensure the optimal calibration, cells are associated to a reconstructed and identified high- p_T object. In order to avoid double counting the objects are considered in a specific order in both directions (x, y) :

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss},jets} + E_{x(y)}^{\text{miss},CellOut} + E_{x(y)}^{\text{miss},\mu} \quad (3.6)$$

where the terms correspond to electrons, photons, τ -leptons, jets, and muons, while the $E_{x(y)}^{\text{miss}, \text{CellOut}}$ term in Eq. 3.6 represents calorimetric cells in topological clusters which are not included in the reconstructed objects.

The magnitude of E_T^{miss} and its direction given by the azimuthal angle are obtained by

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (3.7)$$

$$\phi^{\text{miss}} = \arctan(E_x^{\text{miss}}/E_y^{\text{miss}}). \quad (3.8)$$

Each term in 3.6 is calculated as the negative sum of the calibrated cell energies inside $|\eta| < 4.9$. The muon term, $E_{x(y)}^{\text{miss}, \mu}$, is calculated by the negative sum of the momenta of the muon tracks reconstructed with $|\eta| < 2.7$. If a muon has enough energy to deposit and forms a topo-cluster, to avoid double counting its energy as both due to a jet and due to a muon, the parametrised/measured energy loss is subtracted from the muon momentum, if the muon is a *Combined* one. For the jet term, $E_{x(y)}^{\text{miss}, \text{jets}}$, a simple $|JVF| > 0$ selection is applied. Finally the $E_{x(y)}^{\text{miss}, \text{CellOut}}$ term has already undergone pile-up suppression procedure before entering into the E_T^{miss} calculation. This suppression is based on the *Soft Term Vertex Fraction* (STVF). STVF is the fraction of tracks not matched to physics objects that are associated to the primary vertex (denoted as PV) and are matched to the $E_{x(y)}^{\text{miss}, \text{CellOut}}$ defined as

$$\text{STVF} = \sum_{\text{track, PV}} p_T / \sum_{\text{track}} p_T, \quad (3.9)$$

The tracks for this calculation are selected by applying requirements on the transverse and longitudinal impact parameters ($|d_0| < 1.5\text{mm}$, $|z_0 \cdot \sin\theta| < 1.5\text{mm}$). The term $E_T^{\text{miss}, \text{CellOut}}$ is then multiplied by the STVF factor and the total E_T^{miss} is recalculated. This method corrects the magnitude of the E_T^{miss} and its direction.

The calculation of E_T^{miss} using a calorimeter-based information was the baseline for the 2013 analysis, $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis.

2. Track-based p_T^{miss} :

Even after pile-up suppression the significant pile-up that is present in the data results in a degradation of the resolution of the calorimeter-based E_T^{miss} . It has been proven that an improvement of the order of 20% in this resolution is gained by using a track-based measurement of the soft objects. A track-based E_T^{miss} has been proven to have small dependence on the pile-up. It is useful to suppress the $Z + \text{jets}$ background on the analysis, as well as has a better match to the *true* E_T^{miss} which is the one calculated in simulated Monte Carlo samples, when adding the energies of all the undetected particles, information which is available at truth level.

The track-based E_T^{miss} denoted as p_T^{miss} , is calculated for the soft-objects for which tracks have a transverse momentum larger than 0.5 GeV and are associated to the primary vertex. To achieve this association, further requirements

on the impact parameters, as well as on the number of hits on the Pixel and SCT sub-systems are applied. All the tracks that are associated with a well reconstructed and identified lepton or jet are not included in the p_T^{miss} calculation, since these selected objects are already included separately in the calculation as shown in the Equation 3.5.

The reconstruction of the missing momentum is used by the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis for the mass of the Higgs boson. It is used to provide a better signal resolution relative to the E_T^{miss} especially on the calculation of the transverse mass of the events¹.

Figure 3.7 shows the estimated resolution of E_T^{miss} , p_T^{miss} and the m_T distribution subtracting from the reconstructed quantities the Monte Carlo generated ones. They correspond to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final state with no extra jets present and a significant improvement on the root mean square value of the m_T distribution is observed when using p_T^{miss} instead of E_T^{miss} . Therefore, the updated 2014 spin analysis of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay that is presented in later chapter used this calculation.

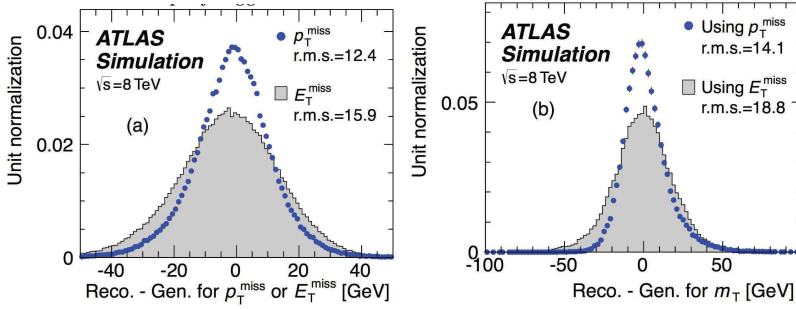


Figure 3.7: Resolutions of the missing transverse momentum (a) and m_T (b) for the gluon-gluon fusion Monte Carlo generated signal in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final state with no jets [39]. The r.m.s. values are in GeV.

In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analyses, the relative missing transverse energy or momentum is used. This is defined as

$$E_{T,\text{rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \cdot \sin\Delta\phi_{\text{near}} & , \text{ if } \Delta\phi_{\text{near}} < \pi/2 \\ E_T^{\text{miss}} & , \text{ otherwise} \end{cases} , \quad (3.10)$$

¹Due to the presence of neutrinos in the final state of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, a fully reconstructed invariant mass is not possible. However, as will also be explained in detail in later chapter a calculation of the transverse mass is possible [101] without the unknown longitudinal neutrino momenta as

$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\nu\nu}|^2}$, where $E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$, $\mathbf{p}_T^{\nu\nu}$ ($\mathbf{p}_T^{\ell\ell}$) is the vector sum of the neutrino (lepton) p_T and $p_T^{\nu\nu}$ ($p_T^{\ell\ell}$) its magnitude.

where $\Delta\phi_{\text{near}}$ is the distance on the azimuthal coordinate of the $\mathbf{E}_T^{\text{miss}}$ and the nearest high- p_T lepton or jet. Similar is the definition for $p_{T,\text{rel}}^{\text{miss}}$.

The uncertainties on the E_T^{miss} calculation are due to two distinct sources: the hard term (high- p_T objects) and the soft term (low- p_T ones). The changes in the hard term (jet energy and lepton momenta) that arise when varying them by their estimated systematic uncertainties are directly propagated on the calculation of E_T^{miss} and they are therefore, fully correlated [102].

On the other hand, the soft term component of the uncertainties on the E_T^{miss} , arise from the modelling of low-energy particle measurements. These low- p_T particles appear as calibrated clusters of cells in the calorimeter that exceed a preset noise level, but they are not matched to any reconstructed physics object. To evaluate the uncertainty, the vector of the missing energy of the soft term have been decomposed into two components: one along the direction of the hard term and one orthogonal to it, thus, the longitudinal and perpendicular directions are defined. The longitudinal direction is sensitive to the simulation modelling of the scale and the resolution of the soft recoil. On the other hand, the perpendicular is a measurement of the resolution of the track-based missing energy calculation and is used so that a systematic on the Monte Carlo resolution can be computed. The two components are then smeared and rescaled to evaluate the associated uncertainties. The overall uncertainties are given as a function of the transverse momentum of the high- p_T objects and are evaluated in terms of the average number of interactions per bunch crossing, μ . The uncertainties are then validated using $Z \rightarrow \mu\mu$ data and Monte Carlo samples. For the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, the mean value of the longitudinal component shows a variation of 0.2–0.3 GeV, where the largest value corresponds to hard objects with $p_T > 60$ GeV. In addition, a variation of 1–4% is evaluated for the resolution of the longitudinal and the perpendicular component, where in this case the largest uncertainty is due to objects with $p_T < 30$ GeV.

3.7 Summary

The objects that are used in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis presented in this thesis have been described in this chapter. The reconstruction and identification criteria used to transform detector signals into physics objects have also been defined. Table 3.1 summarises the selection criteria for the objects. Since both analyses of 2013 and 2014 are in the scope of this thesis, differences in the requirements of the objects between the two publications are described. If a change has been made in the updated 2014 analysis, it is denoted explicitly and written in parenthesis. Otherwise, no change on the requirements should be assumed.

Object	2013 (2014) Requirements
Primary Vertex	Reconstructed Tracks with $p_T \geq 400$ MeV Primary vertex has the max $\sum p_T^2$ of associated tracks.
Trigger	Triggers in "OR" chain : $\begin{cases} \text{EF_e24vhi_medium1} \\ \text{EF_e60_medium1} \\ \text{EF_mu24i_tight} \\ \text{EF_mu36_tight} \\ \text{EF_e12Tvh_medium1_mu8} \end{cases}$
Electrons	<u>Identification</u>: Selection-based <i>tight</i> (LH – based VERY TIGHT, for $10 < E_T < 25$ GeV) (selection – based <i>medium</i>, for $E_T > 25$ GeV) <u>Track-Isolation</u> : $\begin{cases} \sum p_T > 0.9 \text{ GeV} \quad (0.4 \text{ GeV}) \\ d_0 /d_0 < 3.0 \\ z_0 \cdot \sin\theta < 0.4 \text{ mm} \\ \Delta R = \begin{cases} 0.4 & \text{for } p_T^e < 15 \text{ GeV} \\ 0.3 & \text{for } p_T^e > 15 \text{ GeV} \end{cases} \\ \sum_{E_T^e} p_T \begin{cases} < 0.06 & \text{for } 10 < p_T^e < 15 \text{ GeV} \\ < 0.10 & \text{for } p_T^e > 25 \text{ GeV} \end{cases} \end{cases}$ <u>Calorimeter-Isolation</u> : $\sum_{E_T^e} \begin{cases} < 0.20 & \text{for } 10 < E_T^e < 15 \text{ GeV} \\ < 0.28 & \text{for } E_T^e > 25 \text{ GeV} \end{cases}$
Muons	Combined Muons ID+MS <u>Track-Isolation</u> : $\begin{cases} \sum p_T > 1 \text{ GeV} \\ d_0 /d_0 < 3.0 \\ z_0 \cdot \sin\theta < 1.0 \text{ mm} \\ \Delta R = \begin{cases} 0.4 & \text{for } p_T^\mu < 15 \text{ GeV} \\ 0.3 & \text{for } p_T^\mu > 15 \text{ GeV} \end{cases} \\ \sum_{E_T^\mu} p_T \begin{cases} < 0.06 & \text{for } 10 < p_T^\mu < 15 \text{ GeV} \\ < 0.12 & \text{for } p_T^\mu > 25 \text{ GeV} \end{cases} \end{cases}$ <u>Calorimeter-Isolation</u> : $\begin{cases} \text{exclude from } \sum E_T \text{ cells within } \Delta R < 0.05 \text{ around the muon;} \\ \text{apply correction on } N_{PV} \text{ on } \sum E_T; \\ \sum_{p_T^\mu} E_T \begin{cases} < 0.06 & \text{for } 10 < p_T^\mu < 15 \text{ GeV} \\ < 0.10 & \text{for } p_T^\mu > 25 \text{ GeV} \end{cases} \end{cases}$
Jets	EM+JES (LCW + JES) anti-k_T with $dR = 0.04$ $p_T^j \begin{cases} > 25 \text{ GeV} & \text{for } \eta < 2.4 \\ > 30 \text{ GeV} & \text{for } 2.4 < \eta < 4.5 \end{cases}$ $JVF > 0.5$ for $p_T > 50$ GeV and only for $\eta < 2.4$ MV1 b-tagging algorithm at 85% operating point
Missing Energy	Using $E_{T,\text{rel}}^{\text{miss}} (p_{T,\text{rel}}^{\text{miss}})$ calorimeter-based calculation ($p_T > 0.5$ GeV for softTerms from PV)

Table 3.1: Summary of the object requirements.

CHAPTER 4

Theoretical Framework for the properties of the Higgs

For the analyses presented in this thesis, the Standard Model Higgs signal contribution includes the dominant gluon-gluon fusion production process. Since the analyses are performed using events with up to one additional high- p_T jet in the final state, the vector boson fusion, as well as the $t\bar{t}$ and associate production mechanisms are negligible, as discussed in Chapter 1.

The experimental results so far show that the rates of the newly discovered Higgs-like particle are indeed consistent with the Standard Model expectation. However, various alternative models have to be studied in order to validate this observation. Alternative models include the generalised spin-0 nature of the boson, the spin-1 case and a minimal spin-2 model. The most general expressions for each specific spin-dependent model have been tested, following two approaches: the anomalous couplings approach [52] implemented in the 2013 analysis and an effective field theory approach [103], adopted in the 2014 one.

In the following, the most general expressions for each of the two approaches will be presented in terms of the spin hypotheses under study. Starting from the SM case, an expansion to the generalised spin-0 sector will be implemented. This generalisation gives rise to Beyond the Standard Model (BSM) effects under specific parametrisation. Afterwards the most general spin-1 and spin-2 expressions will be introduced, as well as the specific models tested for each one. Finally, at the end of the chapter, the implementation of the theoretical work in terms of tools the event generators will be described.

4.1 Spin-0 Sector

The spin-0 nature of the Higgs boson is mainly studied in the 2014 analysis, in terms of probing the Charge-Parity structure of the scalar boson. In the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay, the sensitivity towards the CP properties of the Higgs boson comes from the

kinematic distribution of the decay products of the W bosons. In addition to the predicted SM scalar boson, there are several BSM interpretations where the parity of the boson is either CP-even or CP-odd [104]. In addition, a very interesting scenario is the one that predicts that the Higgs boson, while it is a mass eigenstate, it is not a CP eigenstate but an admixture of the CP-even and CP-odd states. This scenario introduces CP violation in the Higgs sector. This can be interpreted in the context of the Minimal Super-Symmetric Model (MSSM) [46] or a two Higgs Doublet Model (2HDM) [105]. CP violation in the Higgs sector is related to one of the most interesting open questions that connects the particle physics with cosmology: *Why is there more matter than anti-matter in the universe?*

4.1.1 Spin-0 in the Anomalous Couplings Approach

In the anomalous couplings approach, the interaction of the Higgs with the gauge bosons is described via a scattering amplitude. This amplitude is the most general one, while being consistent with Lorentz invariance, gauge-variance and Bose-symmetry within $SU(3) \times SU(2)_L \times U(1)_R$. In the following, the Higgs-like resonance is denoted by X having four momentum q . The two gauge bosons, denoted as $V = Z, W, \gamma$, have their four-momenta denoted by q_1, q_2 and their polarisation vectors by $\varepsilon_{1,2}$. Finally, the field strength of the gauge bosons is given by the tensor $f^{(i),\mu\nu} = \varepsilon_i^\mu q_i^\nu - \varepsilon_i^\nu q_i^\mu$.

The spin-0 resonance decay amplitude is defined as

$$A(X \rightarrow V_1 V_2) = v^{-1} \left(g_1^{(0)} m_V^2 \varepsilon_1^* \varepsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right), \quad (4.1)$$

where f^* denotes the complex conjugate of the field tensor, $g_{1,\dots,4}^{(0)}$ are invariant form-factors, which can be considered effective dimensionless coupling constants, and finally Λ is the cut-off scale, beyond which new physics may appear.

Different states can be described by selecting values for the form factors $g_{1,\dots,4}^{(0)}$. The SM scalar Higgs boson is obtained when $g_1 \neq 0$. The form factor g_1 is associated with dimension-three operators in the Higgs Lagrangian. In addition, the term g_2 gives the BSM CP-even case, while g_4 describes the BSM CP-odd case. They both are associated to dimension-five operators. Finally, g_3 corresponds to dimension-seven operators and is discarded from the studies.

4.1.2 Spin-0 in the EFT Approach

For the Effective Field Theory approach, the Higgs Characterisation Model [103] is used. The theory is valid up to a certain cut-off scale, Λ , predicting the existence of only a Higgs-like boson having spin J and parity P at the electroweak scale. This means, that any other BSM particles would be found at a scale beyond Λ . With respect to the anomalous couplings approach, the EFT has the advantage of being easily and systematically improved. This is implemented by the addition of higher dimensional operators in the Lagrangian, in a procedure that is similar to perturbation theory. These operators correspond to larger BSM effects. However,

no new physics is assumed below the cut-off scale by construction. For the analyses presented in this thesis is $\Lambda = 1$ TeV.

The Higgs Characterisation Model depends on a modular effective Lagrangian. This Lagrangian includes all the degrees of freedom that are present in the Standard Model, but restricted to values below the Electroweak Symmetry Breaking scale. Therefore, the effective Lagrangian describes the SM without including the Higgs boson. The Higgs sector is represented by an additional bosonic state X which has a specific parametrisation in terms of spin and CP. The Lagrangian can be written as

$$\mathcal{L}_{HC,J} = \mathcal{L}_{SM-H} + \mathcal{L}_J, \quad (4.2)$$

where the two terms correspond to the SM without the Higgs boson, and the spin/CP specific part respectively. The SM case of the Higgs boson can be regained when restricting the interactions with the other SM particles to be described by operators in $\mathcal{L}_J$ of the lowest possible order. On the other hand, BSM effects can be produced either when the operators describing these interactions are of high dimension, or by allowing a mixture of parity states, introducing CP violation in the Higgs sector.

Restricting the gauge bosons to be the SM W , the most general expression for the spin-0 sector is given by

$$\begin{aligned} \mathcal{L}_0^W = & \left\{ c_\alpha \kappa_{SM} [g_{HWW} W_\mu^+ W^{-\mu}] \right. \\ & - \frac{1}{2} \frac{1}{\Lambda} [c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}] \\ & \left. - \frac{1}{\Lambda} c_\alpha [(\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.)] \right\} X_0, \end{aligned} \quad (4.3)$$

where

$$W_{\mu\nu}^\pm = \partial_\mu W_\nu^\pm - \partial_\nu W_\mu^\pm, \quad (4.4)$$

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c, \quad (4.5)$$

and

$$\widetilde{W}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} W^{\rho\sigma}. \quad (4.6)$$

In the SM, the strength of the scalar coupling to the fermions is denoted by $g_{Hff} = m_f/v$, while the pseudo-scalar coupling in a 2HDM with $\tan\beta = 1$ is $g_{Aff} = m_f/v$, where v denotes the vacuum expectation value. In addition, the couplings to the vector bosons follow the same principle as for the fermions. The angle α , for which the cosine (c_α) and sine (s_α) are used in the Lagrangian, parametrises the mixing of the CP states. The κ_i correspond to dimensionless coupling parameters and can be taken to be real without any loss of generality, since they describe CP violation in the most general way.

Apart of the mixing angle α , the four couplings that affect the di- W decay of a Higgs resonance are the κ_{SM} , κ_{HWW} , κ_{AWW} and $\kappa_{H\partial W}$. The κ_{SM} is the coupling to

the Standard Model part of the Lagrangian, while κ_{HWW} and κ_{AWW} are the couplings to the pure BSM CP-even and pure BSM CP-odd states, which are associated with dimension-6 operators in the Lagrangian. Finally, the last coupling, $\kappa_{\text{H}\partial\text{W}}$ is a dimensionless parameter which is independent of α and is associated to derivative operators. The SM scenario can be acquired by requiring $\kappa_{\text{SM}} = 1$, $\kappa_{\text{HWW}} = \kappa_{\text{AWW}} = \kappa_{\text{H}\partial\text{W}} = 0$ and $c_\alpha = 1$. Furthermore, CP violation is introduced when the κ_{HWW} and κ_{AWW} are not vanishing. Table 4.1 gives an example of how pure SM and BSM states can be generated based on a specific choice of the couplings and the mixing angle.

CP Scenario	Coupling Parameters
Standard Model Spin-0 ⁺	$\kappa_{\text{SM}} = 1, \kappa_{\text{HWW}} = \kappa_{\text{AWW}} = \kappa_{\text{H}\partial\text{W}} = 0, c_\alpha = 1$
Pure BSM 0 ⁺	$\kappa_{\text{SM}} = 0, \kappa_{\text{HWW}} = 1, \kappa_{\text{AWW}} = \kappa_{\text{H}\partial\text{W}} = 0, c_\alpha = 1$
Pure BSM 0 ⁻	$\kappa_{\text{SM}} = 0, \kappa_{\text{HWW}} = 1, \kappa_{\text{AWW}} = \kappa_{\text{H}\partial\text{W}} = 0, c_\alpha = 0$
Mixed CP States	$c_\alpha \neq 1$

Table 4.1: Different scenarios based on the spin-0 effective Lagrangian (Eq. 4.3). The pure SM as well as BSM scenarios can be achieved with a specific choice of the couplings. A mixed CP state is obtained when $c_\alpha \neq 0, 1$.

Finally, the derivative operator term, $\kappa_{\text{H}\partial\text{W}}$, gives non-trivial contribution to $\text{H} \rightarrow \text{WW}^* \rightarrow \ell\nu\ell\nu$ decays. The derivative operators are especially important when one of the two W 's of the Higgs decay is off-shell. However, the impact of the derivative term is significantly smaller ($\approx 15\%$) with respect to the variations induced by κ_{HWW} . Our sensitivity to the higher dimensional operators is already very limited, consequently the present statistics would not enable to constrain the effect of the derivative operators. This would require an additional free scan parameter. Consequently, for all the benchmark models, the $\kappa_{\text{H}\partial\text{W}}$ term has been neglected and has been set to zero.

The benchmark models are defined to

- distinguish between SM Higgs and pure BSM CP-even Higgs boson;
- distinguish between SM Higgs and pure BSM CP-odd Higgs boson;
- scan for different CP-mixing between SM Higgs and BSM CP-even Higgs;
- scan for different CP-mixing between SM Higgs and BSM CP-odd Higgs.

Two hypotheses are defined as benchmark models to distinguish between the SM and the pure CP-even (CP-odd) case. Then, two scans are performed on Lagrangian terms to test the compatibility of the data to each choice of the parameters.

In detail, the CP-mixing between the CP-even SM case and a CP-odd BSM Higgs boson will be tested by scanning the parameter

$$\frac{\kappa_{\text{AWW}}}{\kappa_{\text{SM}}} \tan \alpha. \quad (4.7)$$

By choosing $\kappa_{\text{AWW}} = \kappa_{\text{SM}}^1$, without loss of generality, the scan is essentially decomposed into a scan of the mixing angle. Even though the dimensionless couplings κ_i ,

¹ Since the ultimate goal is the shape-based and not rate-based combination of the results between the bosonic channels of ATLAS, a common choice on the value of these couplings should be made. This choice is $\kappa_{\text{AWW}} = \kappa_{\text{SM}} = 1$.

affect both the shape and the rate, it has been shown that all the available phase space can be accessed, in terms of shapes, by simply varying the $\tan\alpha$ values. This is due to the fact that the scanning parameter is the product of the couplings ratio and the $\tan\alpha$. Therefore, the total value for the scanning parameters can be acquired with several combination of the individual terms. This is illustrated in Figure 4.1, where the distribution of the difference in azimuthal angle of the two leptons, $\Delta\phi_{\ell\ell}$, obtained at parton level is plotted. One CP state obtained with two different selections for the individual parameters is shown. The two sets of parameters are $\kappa_{\text{SM}} = 1$, $\kappa_{\text{AWW}} = 2$, $\tan\alpha = 4$ and $\kappa_{\text{SM}} = 1$, $\kappa_{\text{AWW}} = 4$, $\tan\alpha = 2$. The plots are identical.

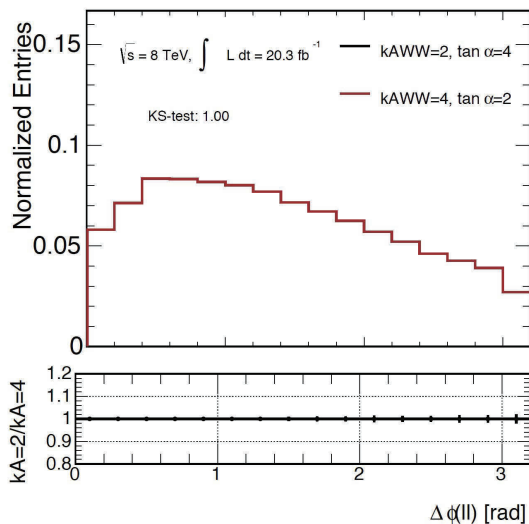


Figure 4.1: Comparison of the opening angle, $\Delta\phi_{\ell\ell}$, obtained with different values of $\tan\alpha$ and κ_{AWW} . The bottom plot shows the ratio of the two distributions. The statistical uncertainty is small. This plot illustrates that any variation of κ_{AWW} can be obtained when scanning $\tan\alpha$.

Furthermore, since the scan on the mixing angle provides the result for the BSM CP-odd mixing, the full range of the $\alpha \in [0, \pi]$ values should be taken into account. This is due to the cosine and sine terms in front of the SM and BSM CP-odd terms in the Lagrangian, which make it not symmetric for positive and negative c_α values. Figure 4.2 shows the comparison of the matrix element distributions calculated for the states with $c_\alpha = \pm 0.1$. The distributions, as expected, do not agree.

On the other hand, the mixing among the CP-even SM and CP-even BSM Higgs bosons depends exclusively on the value of κ_{HWW} and not on the value of α , as in front of both the SM and the BSM part of the Lagrangian there is a c_α term. Therefore to test the mixing of SM and BSM CP-even Higgs bosons, different κ_{HWW} values should be explored and their compatibility with the data studied.

Finally, it should be interesting to verify the case where all the three CP states (i.e. the SM CP-even, the BSM CP-even and the CP-odd Higgs bosons) mix. Unfor-

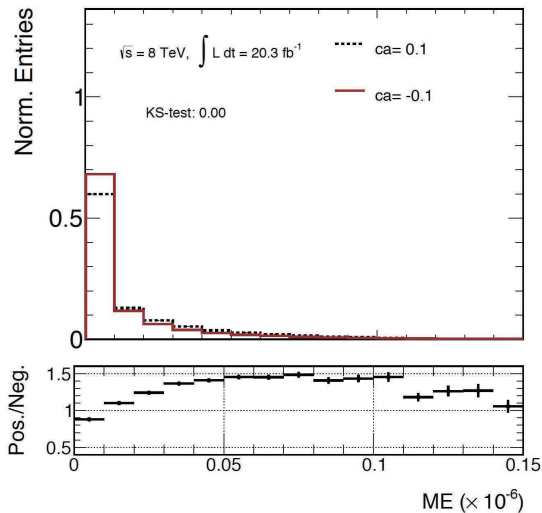


Figure 4.2: Comparison of the matrix element, ME, distribution for both positive and negative values of c_α ($c_\alpha = \pm 0.1$). The bottom plot shows the ratio of the two distributions. Error bars represent the statistical uncertainty.

tunately the present statistics and experimental uncertainties in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ data, limit our possibility to constrain this scenario. A simultaneous scan of $\tan\alpha$ and $\kappa_{H\partial W}$ would be required, which is left for future studies.

4.2 Spin-1 Sector

The scenario of a Higgs-like boson of spin-1 is in principle disfavoured by the observation of the resonance in the $H \rightarrow \gamma\gamma$ channel due to the Landau-Yang theorem [44, 45]. According to this theorem, a spin-1 particle cannot decay into two photons. Furthermore, the spin-1 particle cannot be produced through the fusion of two on-shell gluons. However, in the case that a different resonance is observed in the various decay channels, this hypothesis would not be excluded. Therefore, the study of such a scenario is still interesting. The production mechanism that is considered is only the quark-antiquark ($q\bar{q}$) annihilation.

The study is carried out for the 2013 data set and uses the anomalous couplings approach. The most general scattering amplitude depends on two form factors b_1 , b_2 and is defined as

$$A(X \rightarrow V_1 V_2) = b_1 [(\varepsilon_1^* q)(\varepsilon_2^* \varepsilon_X) + (\varepsilon_2^* q)(\varepsilon_1^* \varepsilon_X)] + b_2 \varepsilon_{\alpha\mu\nu\beta} \varepsilon_X^\alpha \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \tilde{q}^\beta \quad (4.8)$$

where in addition to the other polarisation vectors, ε_X denotes the polarisation vector of the X resonance and $\varepsilon_{1,2}$ the ones corresponding to the vector bosons..

The benchmark models for the spin-1 study are defined with respect to the two form factors. If $b_2 \neq 0$ in Equation 4.8, then the decay amplitude corresponds to a spin-1⁺ exotic pseudo-vector. In addition, if $b_1 \neq 0$ then the decay amplitude corresponds to a spin-1⁻ exotic vector.

4.3 Spin-2 Sector

The need for studying the spin-2 case, arises from the hypothesis that the observed resonance does not correspond to the Higgs boson, but to a graviton. The analysis is based on a spin-2 graviton model with minimal couplings to the SM particles. The polarisation of the graviton with respect to the proton-proton collision axis can only be ± 2 for the gg process and ± 1 for the $q\bar{q}$ process. Therefore, only these two production channels are considered. Electroweak production of the spin-2 resonance should only happen in association to an electroweak boson. From present observations these final states are rare and are therefore neglected. In addition, the gluon-gluon fusion is the dominant process, whereas the $q\bar{q}$ process is contributing with about 4% at leading order in QCD [106]. However, the ratio between the two channels can change significantly when higher-order QCD corrections are taken into account. To address this issue and to parametrise the lack of knowledge, specific benchmark models are studied.

4.3.1 Spin-2 using the Anomalous Couplings Approach

In the anomalous couplings approach, the most general scattering amplitude for a spin-2 particle is given in terms of ten form factors $g_{1\dots 10}$

$$\begin{aligned}
A(X \rightarrow V_1 V_2) = & \Lambda^{-1} \left[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} \right. \\
& + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)} \right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} \\
& + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\varepsilon_1^{*\nu} \varepsilon_2^{*\alpha} - \varepsilon_1^{*\alpha} \varepsilon_2^{*\nu}) \right. \\
& + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \varepsilon_1^{*\alpha} \varepsilon_2^{*\alpha} \left. + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} \right. \\
& + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \varepsilon_{\mu\nu\rho\sigma} \varepsilon_1^{*\nu} \varepsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \varepsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\varepsilon_1^{*\nu} (q \varepsilon_2^*) \right. \\
& \left. \left. + \varepsilon_2^{*\nu} (q \varepsilon_1^*) \right) \right) \left. \right] \quad (4.9)
\end{aligned}$$

where q denotes the momentum with $s = q_1 \cdot q_2$ of the two vector bosons, ε_i the polarisation vectors, $t_{\mu\nu}$ denotes the X wave function given by a symmetric traceless tensor [107] and Λ corresponds to the cut-off scale, the energy up to which the computation is valid. The graviton-like tensor with minimal couplings is obtained when all the form factors g_i are equal to zero, apart from $g_1 = g_5 \neq 0$.

The analysis is performed for several admixtures of the gg and $q\bar{q}$ production mechanisms. The admixtures are described by the factor $f_{q\bar{q}}$, which is

defined as the fraction of $q\bar{q}$ over the gg production. $f_{q\bar{q}}$ ranges from 0% to 100% in steps of 25%.

4.3.2 Spin-2 using the EFT Approach

In the EFT regime of the Higgs Characterisation model, that was used in the 2014 analysis, the effective Lagrangian for a spin-2 minimal couplings resonance is defined by

$$\mathcal{L}_2^p = \sum_{p=V,f} -\frac{1}{\Lambda} \kappa_p T_{\mu\nu}^p X_2^{\mu\nu}, \quad (4.10)$$

where $T_{\mu\nu}^p$ is the energy-momentum tensor and V, f denote the vector bosons and the fermions, respectively. Λ is the cut-off scale which is set to 1 TeV and κ are couplings to vector bosons and fermions. Different values for the couplings to the quarks and the gluons define the production fraction and therefore, the benchmark models studied. The benchmarks include the universal couplings model where $\kappa_g = \kappa_q$, and the non-universal ones with $\kappa_g = 1, \kappa_q = 0$ and $\kappa_g = 0, \kappa_q = 1$. Larger values for these couplings would lead to hard p_T distributions of the di-boson system, which have not been observed [108, 109].

In Leading Order (LO), the $q\bar{q}$ and gluon-gluon fusion production processes are completely independent. However, in the Next-to-Leading Order (NLO), diagrams containing extra partons have contributions from both κ_g and κ_q . The corresponding matrix element contains terms proportional to $(\kappa_q - \kappa_g)^2$, which in fact grows with $s^3/m^3\Lambda^2$ and leads to an enhanced tail in the Higgs p_T distribution. The presence of new physics above the scale Λ may affect the p_T^H distributions below the cut-off scale. The model-dependent nature of the theoretical uncertainty on the p_T scale at which the EFT approach would be corrected by new physics, results in a need to study benchmark models with different p_T^H cut-offs.

Two values are selected:

- the p_T^H should be up to one third of the model cut-off scale, $p_T^H < \Lambda/3 = 1 \text{ TeV}/3 \approx 300 \text{ GeV}$, which is a reasonable assumption within an EFT;
- and without any assumption on the cut-off scale of the model, since the EFT should be valid up to at least the energy scale of the observed resonance, require $p_T^H < 125 \text{ GeV}$.

These selections have no impact on events that do not contain jets in the final state, neither do they affect the universal couplings ($\kappa_g = \kappa_q$) benchmark model. Figure 4.3 shows the p_T^H distribution for the different benchmark models. In (a) the events are restricted to have no jets in the final state, while in (b) only events with exactly one jet in the final state are considered. The impact on the p_T^H tail becomes more apparent in the second case, which due

to the presence of a jet is a NLO effect. Such a behaviour is not observed in the LO case.

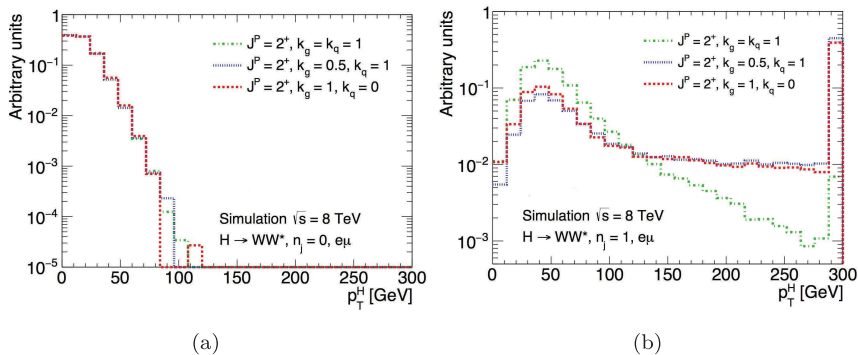


Figure 4.3: Comparison of the shapes of the p_T^H distribution for the different benchmark models considered in the spin-2 study. The distributions shown in (a) for events that have no jet in the final state, while in (b) for events that have exactly one jet in the final state. The effect of the p_T^H tail can be observed only in (b).

4.4 Higgs Signal Generators

In ATLAS the default Monte Carlo generator for the SM Higgs boson production via the gluon-gluon fusion process is POWHEG [110]. When interfaced with PYTHIA8 [111] this generator is able to accurately model jet multiplicities. Furthermore, POWHEG is based on a NLO calculation using finite quark masses in addition to a running-width Breit-Wigner distribution that includes the electroweak corrections at NLO [112–114]. A scale for matching the resummation to the matrix-element calculation that is chosen to reproduce the next-to-next-to-leading order and next-to-leading logarithmic (NNLO+NLL) calculation of the transverse momentum of the Higgs boson [115, 116] is available within POWHEG. All these calculations are presented in detail in [117, 118] and assuming that there is a factorisation between the corrections arising from QCD and electroweak, but they are out of the scope of this chapter. However, POWHEG can only generate SM Higgs signal, and is not designed to generate Higgs boson events under non-SM spin-parity configurations. Therefore, other generators have to be used in the spin/CP studies.

4.4.1 JHU Generator

The JHU [52] generator is used for the signal modelling of the 2013 analysis [119, 120]. The generator implements the anomalous couplings approach,

that is described in the previous sections. It is a leading-order (LO) generator that gives parton-level information including spin and polarisation correlations for the processes of $ij \rightarrow X \rightarrow VV$, where i, j can be quarks or gluons, X is the Higgs boson resonance under a specific spin/CP hypothesis, and V denotes the vector bosons (Z, W, γ).

The spin-1 and spin-2 signal hypotheses are generated with JHU and hadronised with PYTHIA8. In addition, the spin-0 signal samples generated with this generator are only used for cross-checks in the 2013 analysis, since the JHU generator is used for the first time in ATLAS. For validation purposes, a comparison of the SM Higgs sample generated with POWHEG and JHU is done for events without any jets in the final state. Both generators have been interfaced to PYTHIA8 for the parton shower and underlying event modelling, as well as for the hadronisation process. While parton-level studies in the past have shown no significant variations between the two generators when re-weighting the Higgs p_T spectrum of JHU to the NLO POWHEG one, a comparison on the fully simulated samples has to be performed.

Figure 4.4 shows some of the important kinematic distributions in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel, comparing the two samples after the preselection criteria have been applied, without any additional analysis selection requirements. No significant deviation in the variables is observed. Small discrepancies on the shapes of the variables that depend on the missing energy are fully corrected when the selection requirements are also applied.

4.4.2 Madgraph5 Generator

The AMC@NLO_MADGRAPH [121–123] generator was used for the signal modelling of the 2014 analysis [124]. It is a multi-leg matrix-element generator which aims to provide all the necessary elements for phenomenology studies of the SM, as well as of BSM interpretations. It is implementing the EFT approach, hosting modular and easily extendible effective Lagrangians in which the end-user can include or exclude specific terms. AMC@NLO_MADGRAPH also includes a fully automated and optimised NLO calculation both within the SM and at the BSM framework. The calculations are performed combining the FEYNRULES [125] and matrix element programs and is standardised via the Universal FEYNRULES Output (UFO) format. Finally, a merging to showering or hadronisation programs for a complete event that is simulated either at LO, NLO.

Using this generator, the spin-0 and spin-2 signal hypotheses are generated and showered with PYTHIA6.

4.4.3 Matrix Element Re-weighting and Validation

The CP-mixing benchmarks that were described, require a large number of simulated samples: one for each scan point. The full simulation with sufficient statistics for each different value of the parameters scan is impossible. To avoid

this issue, only one mixed sample is generated and then all the other samples are obtained by using a matrix element re-weighting method. This method is applied at truth level exploiting the four momenta of the decay particles from the hard process. In principle, the four momenta of the gluons should be used for the calculation of the matrix element. However, due to the spin-0 nature of the particle and the $2 \rightarrow 1$ process under consideration, the matrix element does not depend on the initial state particle kinematics. In addition, no spin correlations are propagated from the production of the spin-0 resonance to its decay side.

To technically calculate the matrix element for each event, a framework has been developed, which was based on HELicity Amplitudes Subroutines (HELAS) [126]. It reads the truth information at parton level or after showering. When the four momenta of the decay objects have been defined, then the matrix element is computed for one or more Lagrangian configurations. The results can be collected for all the needed configurations in just one run, which makes the analysis time faster.

Afterwards, the re-weighting is based on the matrix element that has been computed for different configurations. Each event is multiplied by a weight which is defined as the ratio of the squared element for the specific event in the Lagrangian configuration of the target state over the original (source) state:

$$w_i = \frac{|ME_{\text{target},i}|^2}{|ME_{\text{source},i}|^2}. \quad (4.11)$$

Matrix element re-weighting technique is a well established technique.

To demonstrate that it was properly applied in our studies, the re-weighting method was tested for the AMC@NLO_MADGRAPH generator. Starting from a mixed CP state, the sample is re-weighted event by event towards both pure CP states. The study is performed at parton level with the initial configuration being $c_\alpha = 0.3$, $\kappa_{\text{SM}} = 1$, $\kappa_{\text{AWW}} = \kappa_{\text{HWW}} = 2$, $\kappa_{\text{H}\theta\text{W}} = 0$, with no additional partons at the initial state. This configuration is the one selected for the signal sample generated with AMC@NLO_MADGRAPH and hadronised with PYTHIA6 that is used for the 2014 analysis. Figure 4.5 shows the matrix element distribution, as well as the $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$ and $p_{\text{T}}^{\ell\ell}$ kinematic distributions for the mixed sample with the $c_\alpha = 0.3$ CP state re-weighted towards the $J^P = 0^+$ state, as well as for the independently generated $J^P = 0^+$ AMC@NLO_MADGRAPH sample. Similarly, Figure 4.6 shows the same distributions for the mixed sample re-weighted towards $J^P = 0^-$, as well as the independently generated $J^P = 0^-$ sample. The shape of the distributions on both figures are almost identical. This is also shown from the ratio plot below each shape comparison plot. Therefore, within the statistical uncertainty the re-weighting procedure performs as expected.

However, this is only validated at parton level until now. The full analysis will be applied on the fully simulated samples after the parton showering and hadronisation, as well as the detector simulation is taken into account. Figure

4.7 shows the matrix element distributions for two re-weighting procedures:

- using $\kappa_{\text{SM}} = \kappa_{\text{HWW}} = \kappa_{\text{AWW}} = 1$ and $\kappa_{\text{H}\partial\text{W}} = 0$ the re-weighting goes from $c_\alpha = 0.3$ towards the $c_\alpha = 0.0$ state;
- using $\kappa_{\text{SM}} = \kappa_{\text{HWW}} = \kappa_{\text{AWW}} = 1$ and $\kappa_{\text{H}\partial\text{W}} = 0$ the re-weighting goes from $c_\alpha = 0.75$ towards the $c_\alpha = 0.5$ state.

The re-weighting is performed first at parton level (labelled in the plots as LHEF, from the Les Houches Files format) and then at the fully simulated sample (labelled in the plots as D3PD). From the two samples, a randomly selected collection of 200,000 events is compared between the two production states. The matrix element distributions for all states agree within statistical uncertainty between the parton and the truth level information. This validates that the matrix element re-weighting can be applied after the parton shower procedure is applied.

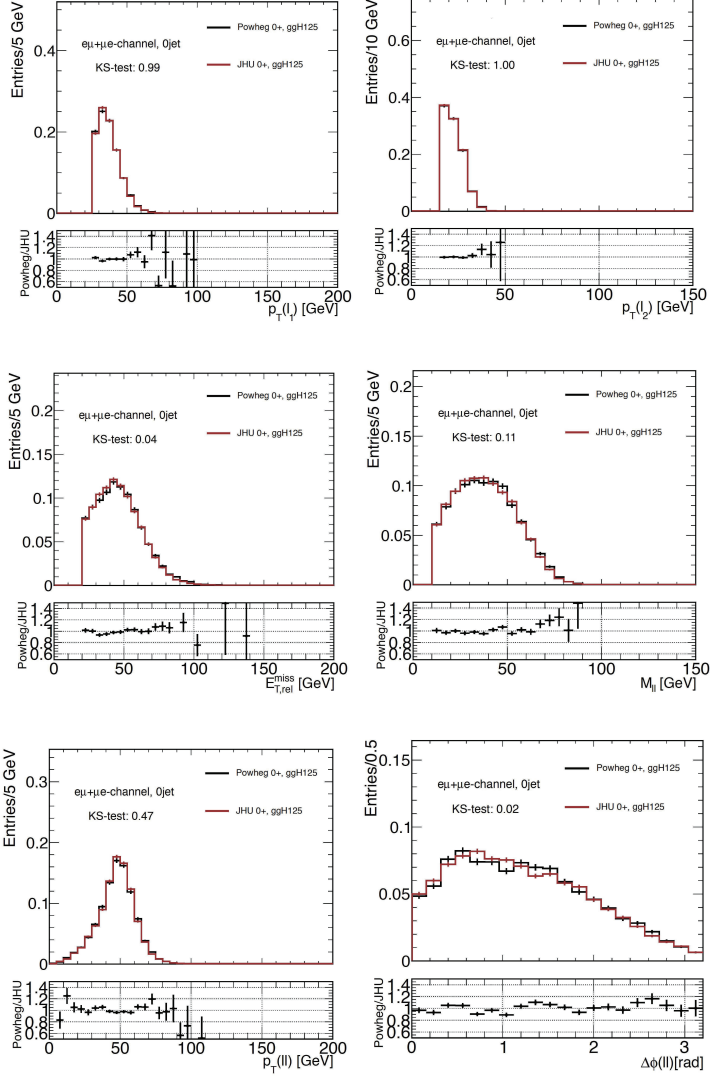


Figure 4.4: Comparison between JHU and POWHEG for a Higgs boson signal with $J^P = 0^+$ in the 0-jet category. The distributions of the transverse momentum of the leading and sub-leading lepton ($p_T^{\ell 1,2}$ respectively), the relative missing transverse energy, $E_{T,\text{rel}}^{\text{miss}}$, the invariant mass, $m_{\ell\ell}$, and transverse momentum, $p_T^{\ell\ell}$, of the dilepton, as well as the opening angle of the two leptons, $\Delta\phi_{\ell\ell}$, distributions are shown. The ratio below compares the shape of POWHEG to the JHU one. The error bars include only the statistical uncertainty. No significant deviation on the shapes of the variables is observed.

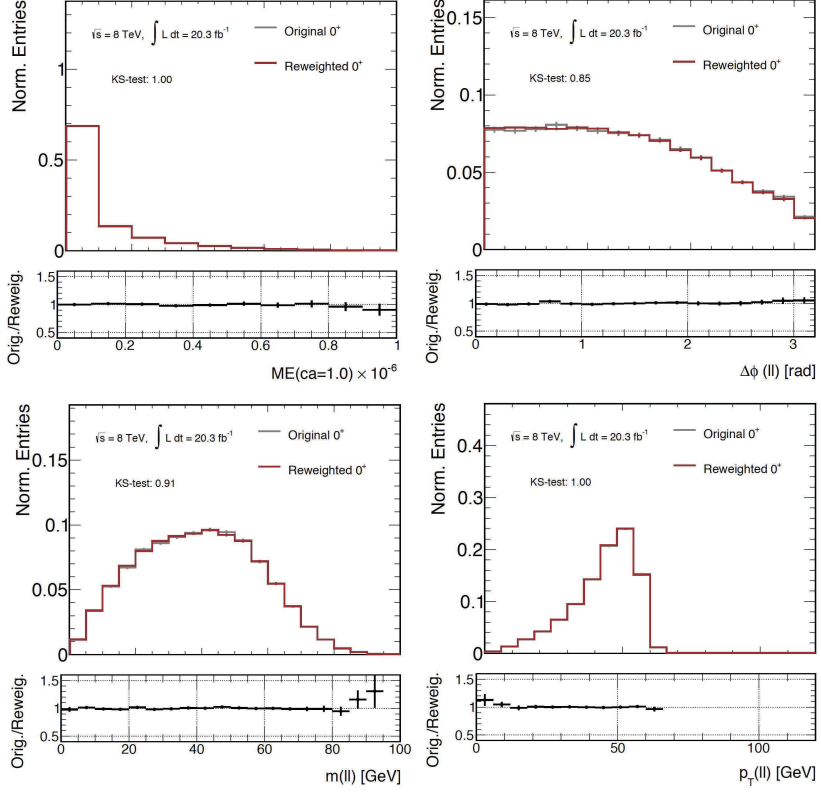


Figure 4.5: Matrix element and parton-level reconstructed $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$ and $p_T^{\ell\ell}$ distributions obtained by generating a CP-even Higgs boson and reweighting towards this CP state from a mixed one. The plot below shows the ratio of the original pure sample to the reweighted one. Error bars illustrate statistical uncertainties.

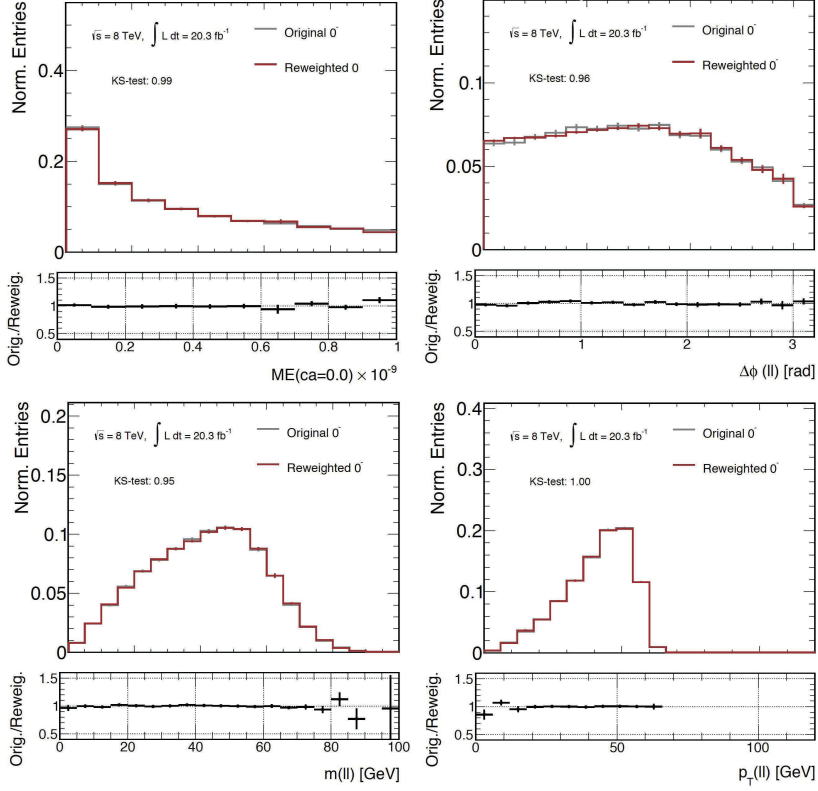


Figure 4.6: Matrix element and parton-level reconstructed $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$ and $p_T^{\ell\ell}$ distributions obtained by generating a CP-odd Higgs boson and reweighting towards this CP state from a mixed one. The plot below shows the ratio of the original pure sample to the reweighted one. Error bars illustrate statistical uncertainties.

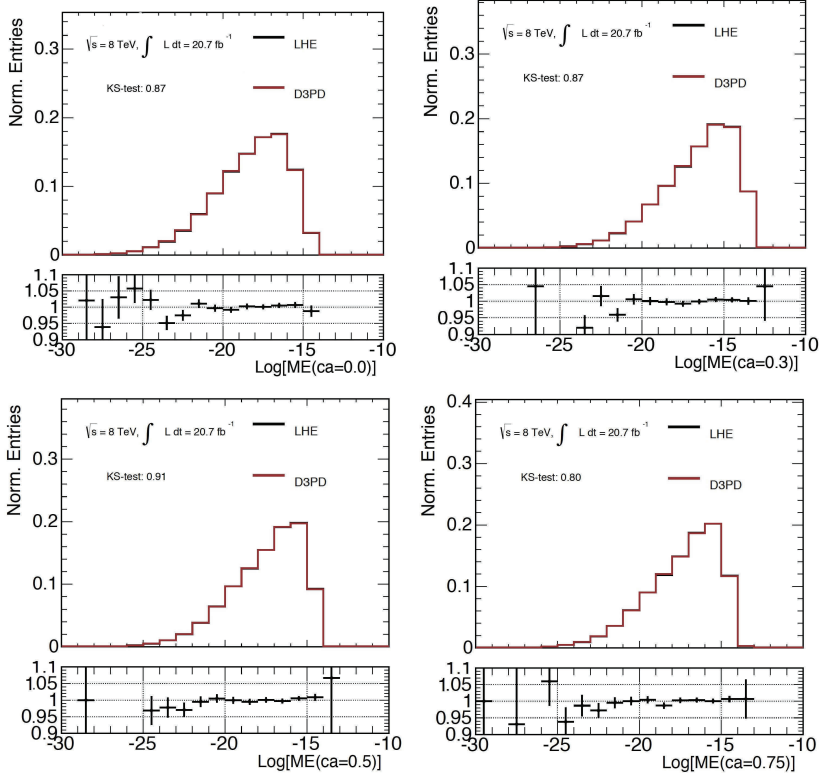


Figure 4.7: Comparison of the matrix element distributions obtained using a parton-level (LHEF) generated sample and after the parton shower with PYTHIA6 (D3PD) for a randomly selected subset of events. The matrix element distributions are calculated for a re-weighting procedure from the CP state with $c_\alpha = 0.3$ towards the CP state with $c_\alpha = 0.0$ (top), and one from the CP state with $c_\alpha = 0.75$ towards $c_\alpha = 0.5$. Error bars include statistical uncertainty.

4.4.4 Mapping Between the Two Approaches

The EFT approach implemented in AMC@NLO_MADGRAPH and the anomalous couplings in JHU should provide the same results. In addition, the goal of ATLAS for the CP-mixing analysis is to combine the results of $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. Since the former used the anomalous approach and the latter the EFT one, a conversion table should exist between the two. Indeed the conversions for the JHU formalism (Eq. 4.1) to the AMC@NLO_MADGRAPH one (Eq. 4.3) are found to be

$$\begin{aligned} g_1 &= 2i \times \kappa_{\text{SM}} \times c_\alpha, \\ g_2 &= 2i \times \tilde{\kappa}_{HVV} \times c_\alpha, \\ g_3 &= 0, \\ g_4 &= 2i \times \tilde{\kappa}_{AVV} \times s_\alpha, \end{aligned} \tag{4.12}$$

where

$$\tilde{\kappa}_{XVV} = \frac{1}{4} \frac{v}{\Lambda} \kappa_{XVV} = 0.49 \cdot \kappa_{XVV}. \tag{4.13}$$

$\tilde{\kappa}_{XVV}$ in Eq. 4.13 can be either $\tilde{\kappa}_{HVV}$, for the CP-even, or $\tilde{\kappa}_{AVV}$ for the CP-odd scenario, for any diboson (VV) final state. In addition, v denotes the vacuum expectation value of the Higgs field.

Using this mapping, it is simple to switch from the settings used in one generator to the other and the same distributions should be obtained. To verify this, a sample of 200,000 events has been generated with AMC@NLO_MADGRAPH with the following settings $\kappa_{\text{SM}} = 1$, $\kappa_{\text{HWW}} = 1$, $\kappa_{\text{AWW}} = 2$, $\Lambda = 125.5$ GeV, $c_\alpha = 0.3$. This has been compared with a JHU sample of equal size, generated using $g_1 = 0.6$, $g_2 = 0.6i$, $g_3 = 0$, $g_4 = 1.9$. The study has been performed at generator level in the Higgs rest frame, comparing the Cabbibo and Maksymowicz variables. In Figure 4.8 the invariant mass of the most energetic, on-shell W boson, as well as the θ_1, θ_2 and Φ decay angles are shown. The two generators comfortably agree within the statistical uncertainties.

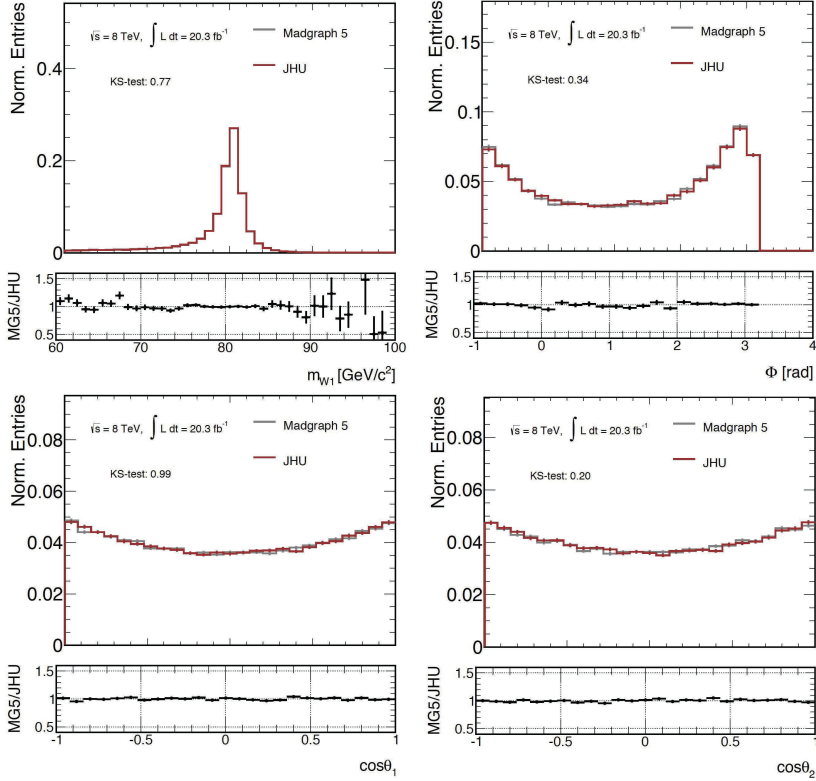


Figure 4.8: Comparison between JHU and AMC@NLO_MADGRAPH generators for the parton level distributions of the on-shell mass of the W bosons and the three decay angles in the Higgs rest frame. The lower plots show the ratio of the AMC@NLO_MADGRAPH to JHU distributions. Error bars represent the statistical uncertainty. All distributions agree within statistical errors.

Event Selection and Background Processes

The object reconstruction and identification that was discussed in Chapter 3 performs the primary selection of physics objects for the analysis that follows. A selection has to be performed based on the kinematics and the topology of the events in order to disentangle the signal from the background processes. As a first step an event preselection based on the primary characteristics of the physics objects that are present in the signal events is performed. After, the event selection is applied exploiting the full topological and kinematical information of the events.

Several background processes in the Standard Model can fake a $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal candidate. The composition of the background varies with the selected topology and the kinematics of the events. The dominant background processes are the non-resonant WW decays, the leptonic decays of top-quarks ($t\bar{t}$, tW , tb , tqb), the decay of Z/γ^* into a τ lepton pair and the W + jets process where the W is produced associated with a jet that is misidentified as a lepton, or dijet, multi-jet production with two misidentifications. Smaller contributions are given by the non- WW dibosons ($W\gamma$, $W\gamma^*$, WZ and ZZ) background, as well as the very small $Z/\gamma^* \rightarrow ee/\mu\mu$ contribution.

The background modelling of the dominant background processes is crucial for the analysis. Since, all the dominant background processes in the analysis, apart from the W + jets process, are dependent on Monte Carlo simulated samples, the simulation of the physics processes should model the data properly. This is verified in background enriched regions of the phase space, which are usually orthogonal to the signal enriched region (SR). These regions are usually referred to as Control Regions (CRs). A total normalisation factor for each background can be extracted from the respective control region.

This chapter will focus on the signal region and the control regions definitions in terms of kinematic and topological characteristics for the two analyses (2013 and 2014). The same dataset is used in both analyses, with a total integrated luminosity of 20.7fb^{-1} for the 2013 and 20.3fb^{-1} for the 2014. In the next section, the Monte Carlo generators used for the modelling of background processes will be introduced. Since the control regions are orthogonal, in terms of selection, to the signal region, preselection and selection criteria used in the signal region will be introduced. Finally, the full background composition will be discussed, as well as the treatment of the dominant background processes in their respective control regions.

5.1 Modelling of the Background Processes

While the W +jets and multi-jet background processes are estimated using data, all other background processes have dedicated Monte Carlo simulated samples. Overall, most of the samples are generated using the POWHEG [110] generator which includes NLO corrections as discussed also in the signal modelling chapter (Chapter 4). For higher parton multiplicities, ALPGEN [127] and SHERPA [128] are used. In a few cases only LO generators are available, where ACERMC [129] or GG2VV [130] are used.

After the matrix-element-level generation is done, the matching to model the parton shower, underlying event and hadronisation is done using either PYTHIA6 [131], PYTHIA8 [111], HERWIG [132] or SHERPA. When HERWIG is used, JIMMY [133] handles the modelling of the underlying event. The parton distribution functions (PDFs) that are used for the POWHEG, MC@NLO [134] and SHERPA samples are taken from CT10 [135], while for the ALPGEN+HERWIG, MADGRAPH [122] and ACERMC samples from CTEQ6L1 [136]. Finally, the $Z/\gamma^* + \text{jets}$ sample is re-weighted to the MRST PDF set [137].

The underlying event and minimum bias effect are modelled by PYTHIA. The detector response is simulated [138] by the GEANT4 [139] full simulation, or a parametrised GEANT4-based calorimeter simulation [140].

In terms of cross-section calculation, the inclusive WW one is calculated at NLO using MCFM [141]. The non-resonant gluon fusion is calculated and modelled at leading order in terms of α_S with GG2VV for both WW and ZZ , as well as their interference. In addition the $t\bar{t}$ production cross-section is normalised to the NNLO in α_S , while the resummation of higher-order terms to NNLL accuracy is evaluated with TOP++2.0 [142].

For the $W\gamma^*$ background process, different generator schemes are used if the invariant mass of the two opposite-sign leptons from the decay is larger than 7 GeV or not. For $m_{\ell\ell} > 7$ GeV, POWHEG+PYTHIA8 is used, while for $m_{\ell\ell} < 7$ GeV either MADGRAPH+PYTHIA(2013) or SHERPA(2014) are used due to their capability to model invariant masses down to the production threshold.

Tables 5.1 and 5.2 summarise the Monte Carlo used for the generation, as

well as for the underlying event, parton shower and hadronisation modelling of the background processes in 2013 and 2014 analysis.

Process	Generator
$q\bar{q}/g \rightarrow WW$	POWHEG+PYTHIA8
$gg \rightarrow WW$	GG2WW [130]+HERWIG
$t\bar{t}, tW, tb$	MC@NLO+HERWIG
tqb	AcerMC [129]+PYTHIA
$Z/\gamma^*(+jets)$	ALPGEN+HERWIG
$Z^{(*)}Z^{(*)} \rightarrow 4l$	POWHEG+PYTHIA8
$W(Z/\gamma^*)(m_{Z/\gamma^*} > 7 \text{ GeV})$	POWHEG+PYTHIA8
$W(Z/\gamma^*)(m_{Z/\gamma^*} < 7 \text{ GeV})$	MADGRAPH+PYTHIA
$W\gamma$	ALPGEN+HERWIG

Table 5.1: Summary of the simulated background samples that are used in the 2013 analysis. The process and the corresponding programs for the generation, hadronisation and parton shower and underlying event modelling are shown.

Process	Generator
$q\bar{q}/g \rightarrow WW$	POWHEG+PYTHIA6
$gg \rightarrow WW$	GG2WW [130]+HERWIG
$t\bar{t}$	POWHEG+PYTHIA6
Wt	POWHEG+PYTHIA6
$tq\bar{b}$	AcerMC+PYTHIA6
$t\bar{b}$	POWHEG+PYTHIA6
$W\gamma (p_T^\gamma > 8 \text{ GeV})$	ALPGEN+HERWIG
$W\gamma^* (m_{\ell\ell} \leq 7 \text{ GeV})$	SHERPA
$WZ (m_{\ell\ell} > 7 \text{ GeV})$	POWHEG+PYTHIA8
$Z\gamma (p_T^\gamma > 8 \text{ GeV})$	SHERPA
$Z\gamma^* (\min m_{\ell\ell} \leq 4 \text{ GeV})$	SHERPA
$ZZ (m_{\ell\ell} > 4 \text{ GeV})$	POWHEG+PYTHIA8
$ZZ \rightarrow \ell\ell\nu\nu (m_{\ell\ell} > 4 \text{ GeV})$	POWHEG+PYTHIA8
$Z/\gamma^* (m_{\ell\ell} > 10 \text{ GeV})$	ALPGEN+HERWIG

Table 5.2: Summary of the simulated background samples that are used in the 2014 analysis. The process and the corresponding programs for the generation, hadronisation and parton shower and underlying event modelling are shown.

5.2 Event Preselection

A signal candidate in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay consists of a pair of W bosons decaying leptonically into two oppositely charged leptons (electrons or muons) and two neutrinos, manifesting themselves in the final state as large transverse energy imbalance. The preselection requirements are designed to reduce substantially the major background processes to the Higgs-boson signal.

The lepton with the highest momentum (*leading lepton*), which is also the triggering object, is required to have $p_T > 22$ GeV. This was changed with respect to the $p_T > 25$ GeV of the 2013 analysis. The sub-leading lepton p_T is required to be above 15 GeV. The selection of candidates is the same as for the analysis studying the couplings of the Higgs boson decaying into a pair of W bosons [39].

After the lepton preselection, four major sources of backgrounds are identified to be : W + jets, Drell-Yan, top quark and non resonant diboson production. To further suppress the Drell-Yan background, mainly the $Z \rightarrow \tau\tau \rightarrow \ell\ell + E_T^{\text{miss}}$, in the events where the leptons in the final state are of different flavour, the invariant mass of the dilepton system is required to be greater than 10 GeV. The missing transverse energy from this background process tends to be small with respect to the expected E_T^{miss} from the signal process. As described in Chapter 3 the definition of the missing transverse energy was changed between the 2013 and 2014 analysis, from $E_{T,\text{rel}}^{\text{miss}}$ to p_T^{miss} , which is more performing in high pile-up conditions. A selection of events with $E_{T,\text{rel}}^{\text{miss}} > 20$ GeV for the 2013 analysis and $p_T^{\text{miss}} > 20$ GeV for the 2014 one is applied to further suppress the Drell-Yan component of the background composition. This selection also reduces the W + jets background, since it also has smaller missing transverse energy component.

Finally as far as the jets are concerned, a signal event must contain at most one jet with $p_T > 25$ GeV and $|\eta| < 4.5$. The transverse momentum of the jet is required to be higher than 30 GeV in the forward region ($2.4 < |\eta| < 4.5$) in order to minimise the effect of the pile-up. The absolute value of the jet vertex fraction ($|JVF|$) is required to be 0.5 for jets with $p_T < 50$ GeV and $|\eta| < 2.4$, mainly to suppress the pile-up jets in the central region.

Figures 5.1 and 5.2 show Monte Carlo simulated distributions for some kinematic variables used later to define the signal and control regions. Namely, the azimuthal angle of the two leptons, $\Delta\phi_{\ell\ell}$, the reconstructed transverse invariant mass of the event, m_T , the invariant mass, $m_{\ell\ell}$, and the transverse momentum, $p_T^{\ell\ell}$, of the dilepton, as well as the reconstructed invariant mass of the $Z/\gamma^* \rightarrow \tau\tau$ system are shown. The latter is reconstructed using the approximation that the neutrinos are collinear with the visible products of the corresponding τ decays and assuming that the leptons arise from the $Z/\gamma^* \tau\tau$ decays. The distributions are shown after the preselection requirements have been applied. The backgrounds are stacked on top of each other and the red histogram represents the Standard Model Higgs-boson signal with $m_H = 125$ GeV.

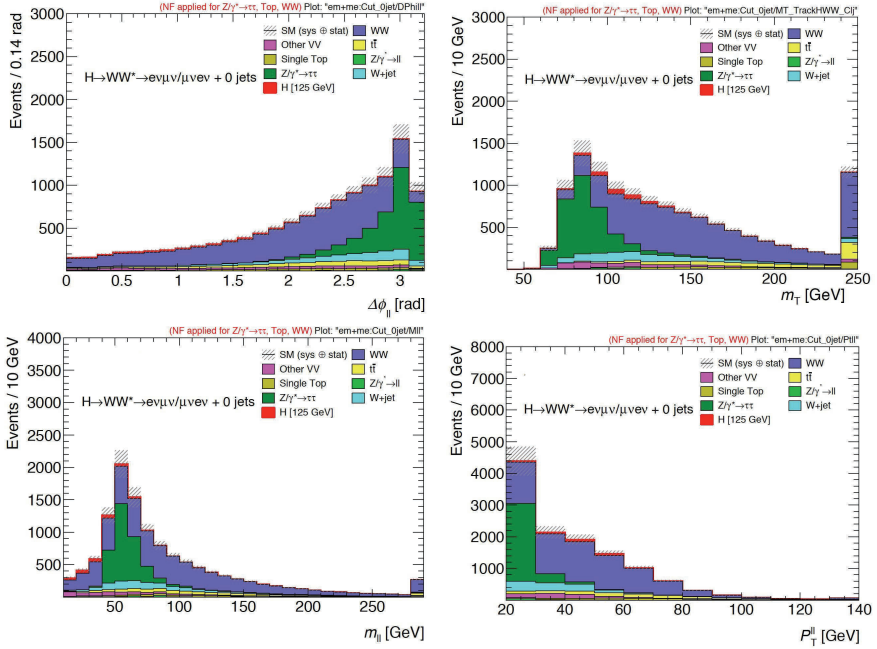


Figure 5.1: Fully simulated Monte Carlo distributions for some of the variables that are used later in the event selection, namely $\Delta\phi_{\ell\ell}$, m_T , $m_{\ell\ell}$ and $p_T^{\ell\ell}$. The preselection requirements are applied. In addition, the final state with no jets is shown. The stacked signal is assumed to be a SM Higgs boson with $m_H = 125$ GeV. The normalisation factors from the control regions are applied. The gray hashed area shows the statistical and systematic uncertainties.

5.3 Event Selection

After the preselection, the signal events are classified in *jet-bins*, based on the number of jets in the final state. A signal event may have none, one and two or more jets in its decay signature. In each of the jet categories, the events are further split depending on the flavour of leptons. If the two leptons from the W decays are of the same flavour, the event is categorised as *same flavour* (SF) event, while if they are of different flavours, the event is categorised as *different flavour* (DF).

The categorisation in jet-bins is mainly driven from the differences in the main production mechanism and the composition of the backgrounds in events with different jet topologies. For the 0-jet events, the gluon-gluon fusion is the main production mechanism (96%) for which the major background is the irreducible non-resonant WW pair production. However, the situation changes when events with 1-jet in the final state are selected. While gluon-gluon fusion remains the major production mode, ($\approx 80\%$), the percentage of events arising

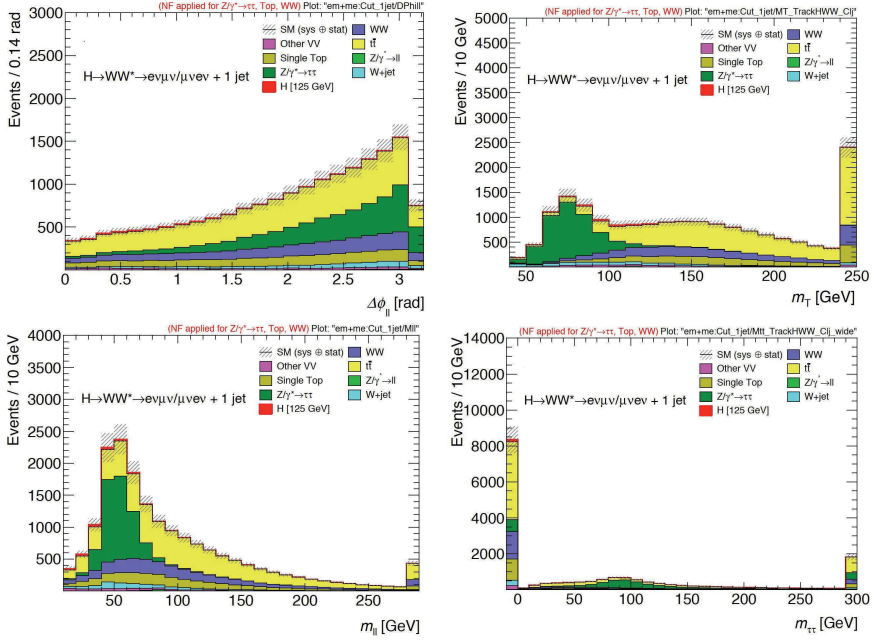


Figure 5.2: Fully simulated Monte Carlo distributions for some of the variables that are used later in the event selection, namely $\Delta\phi_{\ell\ell}$, $m_{\tau\tau}$, $m_{\ell\ell}$ and $m_{\tau\tau}$. The pre-selection requirements are applied. In addition, the final state with exactly one jet is shown. The stacked signal is assumed to be a SM Higgs boson with $m_H = 125$ GeV. The normalisation factors from the control regions are applied. The gray hashed area shows the statistical and systematic uncertainties.

from vector-boson fusion production are not negligible ($\approx 15\%$). In addition, the impact of top leptonic decays is larger in the 1-jet bin ($\approx 30\%$ of the total events). Events with two or more jets in the final state are not considered in the analysis.

Furthermore, the categorisation into SF and DF is due to the fact that DF events have higher purity with respect to SF ones, which suffer from large background contamination mainly from the $Z/\gamma^* \rightarrow ee/\mu\mu$ process. Therefore, the expected sensitivity for the different flavour was better than the same flavour one.

For the needs of the spin and CP analysis in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final state, the different flavour events in the 0-jet bin were used for the 2013 analysis. For the updated 2014 analysis the different flavour events of the 0 and 1 jet bin categories have been used. In order to distinguish among different spin and CP properties of the Higgs boson, the analysis discussed hereafter has major differences with respect to the one developed for the study of the Higgs couplings [39]. In addition, in the analysis the observed resonance is tested against

the Standard Model spin-0 hypothesis and the alternative spin-1 $^\pm$ and spin-2 $^+$ ones, the signal events containing this resonance should be separated from the background processes. The separation between the different signal hypotheses should be done with the minimum possible bias. Therefore, comparing with the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ couplings analysis, some of the preselection requirements had to be loosened in order for the acceptance of alternative signal hypotheses to be increased. Figure 5.3 shows the normalised to unity simulated distributions of the relative missing transverse energy, the $p_T^{\ell\ell}$, the $\Delta\phi_{\ell\ell}$ and the $m_{\ell\ell}$ distributions that are used in the event selection for $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ events under the hypotheses that the Higgs boson has spin-0 $^+$, spin-1 $^\pm$ spin-2 $^+$.

After the requirements in the 0- and 1-jet bins are presented, Table 5.3 summarises the preselection and selection requirements for both analyses. If specific changes have been made between the two analyses, they are mentioned explicitly. The event selection is discussed in detail in the next subsections, while plots and tables with the event yields for the two analyses are given in Section 5.5.

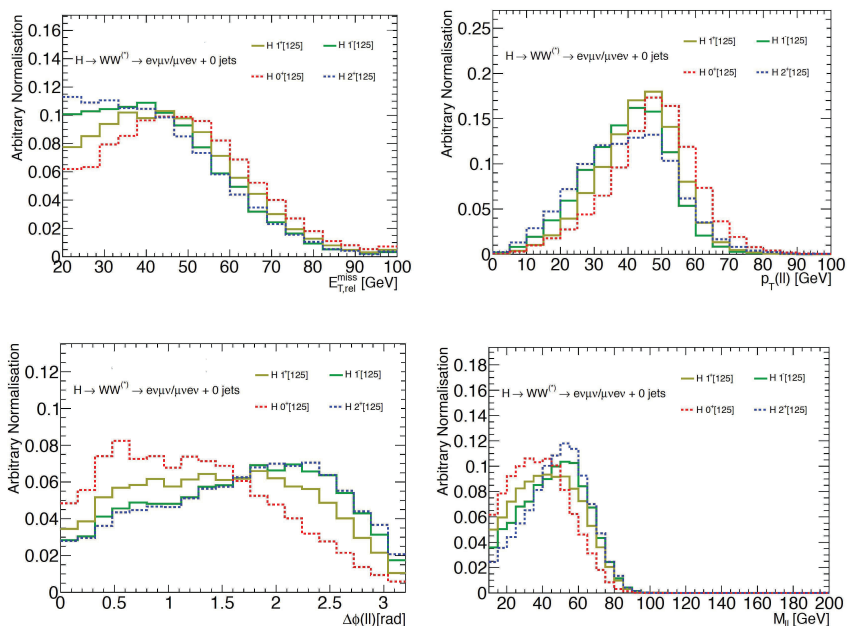


Figure 5.3: The normalised to unit area shape distributions for the $E_{T,rel}^{miss}$, $p_T^{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ variables, under the assumption of a Standard Model (red dashed), a spin-1 $^+$ (solid gold), a spin-1 $^-$ (solid green) and a spin-2 $^+$ (dashed blue) Higgs-boson signal.

5.3.1 0-jet bin Event Selection

Taking the acceptance of the alternative hypotheses into account, for the selection in the 0-jet bin, a threshold of 20 GeV is set on the transverse momentum of the dilepton system to reduce the Drell-Yan background process. A further reduction of the Drell-Yan and non-resonant WW background is achieved by requiring $\Delta\phi_{\ell\ell} < 2.8$, since background events have larger $\Delta\phi_{\ell\ell}$ values than signal ones, due to the different spin correlations discussed in Chapter 1. Finally, a requirement on the invariant mass of the dilepton system is made to suppress the non-resonant WW background. The threshold is set at $m_{\ell\ell} < 80$ GeV.

5.3.2 1-jet bin Event Selection

In the final state with exactly one jet, since the background composition changes, the kinematic requirements of the signal events should also change with respect to the 0-jet bin selection.

To reject the contribution of the top-quark related backgrounds, events with b -quark jets with $p_T > 20$ GeV and identified with the MV1 b -tagging algorithm at the 85% operating point are vetoed. An additional veto on the invariant mass of the di-tau system, $m_{\tau\tau}$ is applied, to reduce the $Z/\gamma^* \rightarrow \tau\tau$ background process. The $m_{\tau\tau}$ is reconstructed using the approximation that the neutrinos are collinear with the visible products of the corresponding τ decays and assuming that the leptons arise from $Z/\gamma^* \rightarrow \tau\tau$ decays. For the veto, if the energy fractions carried by the visible decay products are positive and the $\tau\tau$ invariant mass satisfies the $m_{\tau\tau} > m_Z - 25$ GeV requirement, the event is rejected.

Furthermore, to reject the W +jets background, the transverse mass of single leptons m_T^ℓ , which is defined as the $m_T^{\ell_i} = \sqrt{2p_T^{\ell_i}p_T^{\text{miss}}(1 - \cos\Delta\phi)}$, where $\Delta\phi$ is the angle between the lepton transverse momentum and p_T^{miss} , is introduced. The largest transverse mass of the leptons in the event is required to satisfy $m_T^\ell > 50$ GeV. An additional cut on the transverse mass of the whole event, $m_T < 150$ GeV, is applied to reduce WW and top backgrounds.

Finally, the same selection on $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ is performed as for the 0-jet bin to suppress the respective background processes.

5.4 Backgrounds

A short description of the background processes has already been introduced. In this section, the dominant background sources, as well as the way they are treated in the analysis are discussed. Table 5.4 gives a summary of all the background processes and their features that can fake a $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signal candidate. In addition, Figure 5.4 [39] shows the composition of signal and background processes in terms of percentage of the total (i.e. signal and

Variable	Requirements 2014 (2013)
Preselection	
N_{leptons}	Exactly 2 with $p_T > 10$ GeV, $e\mu$, opposite sign
$p_T^{\ell_1}$	> 22 GeV (> 25 GeV)
$p_T^{\ell_2}$	> 15 GeV
$m_{\ell\ell}$	> 10 GeV
$p_T^{\text{miss}} (E_T^{\text{miss}})$	> 20 GeV
0-jet selection	
$p_T^{\ell\ell}$	> 20 GeV
$m_{\ell\ell}$	< 80 GeV
$\Delta\phi_{\ell\ell}$	< 2.8
p_T^H	< 125 or 300 GeV (*) (only for 2014)
1-jet selection (only for 2014)	
b -veto	No b -jets with $p_T > 20$ GeV
$m_{\tau\tau}$	$< m_Z - 25$ GeV
m_T^ℓ	> 50 GeV
$m_{\ell\ell}$	< 80 GeV
$\Delta\phi_{\ell\ell}$	< 2.8
m_T	< 150 GeV
p_T^H	< 125 or 300 GeV (*)

Table 5.3: Summary list of the preselection and selection requirements for the signal region adopted in the 2013 and 2014 analyses presented in this thesis. The table refers to the latest (2014) analysis, but if a requirement was different in the 2013 spin analysis, it is stated explicitly. The p_T^H requirements (*) is applied only in the 2014 analysis for the spin-2 benchmarks with non-universal couplings.

background) event yields in the different flavour category for 0 and 1 jet-bin categories.

5.4.1 Overview of Treatment of Background Processes

Small backgrounds, such as non- WW dibosons ($W\gamma$, $W\gamma^*$, WZ and ZZ) and $Z/\gamma^* \rightarrow e^+e^-$ or $\mu\mu$ are estimated directly from simulation taking into account the appropriate theoretical corrections. These corrections include the cross-section calculations and event modelling, mainly due to next-to-leading order effects.

As far as the dominant backgrounds are concerned, these include

- non-resonant W -boson pair production;
- top-quark pair production and single-top-quark production;
- misidentified leptons from a W + jets or a multi-jet production with misidentified leptons;

Name	Process	Features
WW	WW	Irreducible
Top Quarks		
$t\bar{t}$	$t\bar{t} \rightarrow WbW\bar{b}$	Unidentified b -quarks
t	tW	Unidentified b -quark
	$t\bar{b}, tq\bar{b}$	q or b misidentified as ℓ ; unidentified b -quarks
Misidentified leptons (Misid.)		
Wj	$W + \text{jets}$	j misidentified as ℓ ;
jj	Multijet production	jj misidentified as $\ell\ell$; misidentified neutrinos;
VV	$W\gamma$	γ misidentified as e
	$W\gamma^*, WZ, ZZ \rightarrow \ell\ell\ell\ell$	Unidentified lepton(s)
	$ZZ \rightarrow \ell\nu\nu$	Irreducible
	$Z\gamma$	γ misidentified as e ; unidentified lepton
Drell-Yan (DY)		
$ee/\mu\mu$	$Z\gamma^* \rightarrow ee, \mu\mu$	Misidentified neutrinos
$\tau\tau$	$Z\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu$	Irreducible

Table 5.4: Background processes to the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis. Irreducible backgrounds have exactly the same final state signature as the signal process; other backgrounds have specific features which can be misidentified as signal signatures.

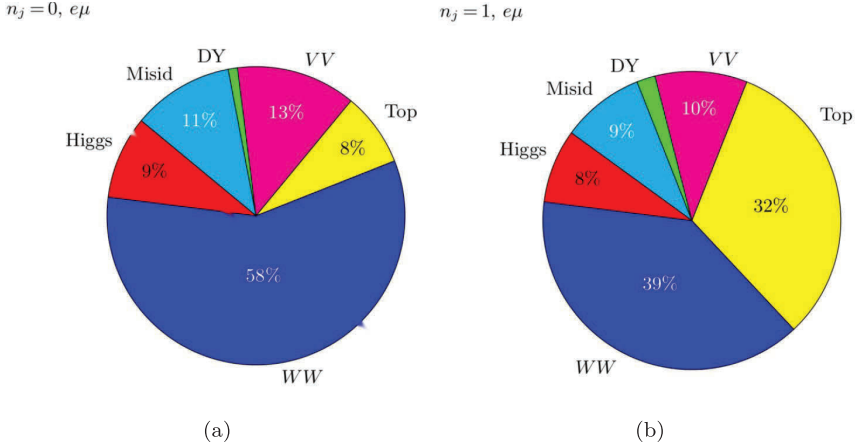


Figure 5.4: Sample composition for the different flavour events in the $\sqrt{s} = 8$ TeV data for the 0-jet bin (a) and the 1-jet bin (b) category.

- $Z\gamma^*$ to $\tau\tau$ final states.

These background sources are normalised to the observed data either by using

data-driven methods, such as in the case of the $W + \text{jets}$ background, or using the observed data yields in their respective background enriched control regions. The control regions are defined to be orthogonal to the signal region in order to minimise the extrapolation uncertainties from the control regions to the signal regions. The control regions that are used in the spin/CP analysis of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ are listed in Table 5.5.

Control Region	Selection
WW CR 0-jet	Preselection, $p_T^{\ell\ell} > 20$ GeV, $80 < m_{\ell\ell} < 150$ GeV
WW CR 1-jet	Preselection, b -veto, $m_{\tau\tau} < m_Z - 25$ GeV, $m_T^\ell > 50$ GeV, $m_{\ell\ell} > 80$ GeV
Top CR 0-jet	Preselection, $\Delta\phi_{\ell\ell} < 2.8$, all jets inclusive
Top CR 1-jet	At least one b -jet, $m_{\tau\tau} < m_Z - 25$ GeV
$Z/\gamma^* \rightarrow \tau\tau$ CR 0-jet	Preselection, $m_{\ell\ell} < 80$ GeV, $\Delta\phi_{\ell\ell} > 2.8$
$Z/\gamma^* \rightarrow \tau\tau$ CR 1-jet	Preselection, b -veto, $m_T^\ell > 50$ GeV, $m_{\ell\ell} < 80$ GeV, $ m_{\tau\tau} - m_Z < 25$ GeV

Table 5.5: Definition of control regions that are used in the Spin and Parity analysis for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay mode. For the 2013 analysis only the 0-jet bin was used, while for the 2014 analysis both 0 and 1 jets categories were used with the respective control regions.

In order to normalise the background prediction in the respective control region, a normalisation factor β is determined by the ratio of the observed to expected yields of this background in the control region. For example, in the WW CR, the observed event yield is obtained by subtracting from the data the non- WW contributions. The background estimate in the signal region is defined per background as

$$B_{\text{SR}}^{\text{est}} = B_{\text{SR}} \cdot \underbrace{N_{\text{CR}}/B_{\text{CR}}}_{\text{Normalization } \beta} = N_{\text{CR}} \cdot \underbrace{B_{\text{SR}}/B_{\text{CR}}}_{\text{Extrapolation } \alpha}, \quad (5.1)$$

where the terms N_{CR} and B_{CR} are the observed and Monte Carlo estimated event yields in the control region respectively, while B_{SR} denotes the Monte Carlo estimate in the signal region. The two ratios define the data-to-Monte-Carlo normalisation factor β in the control region and the extrapolation factor, α , from the control region to the signal region predicted by the simulation. Since these factors are estimated in the background enriched region, under the assumption of large event yields (i.e. enough statistics), the large theoretical uncertainties on the background estimate can be decomposed in two significantly smaller uncertainties: the statistical component of the uncertainty, that is attributed on the number of observed event yields in the control region, N_{CR} , and the systematic uncertainties on the extrapolation factor, α .

For some of the dominant backgrounds, except for the normalisation systematic uncertainty, an additional shape uncertainty has to be taken into account. This uncertainty covers the shape variations of a specific background

in terms of the fitted discriminant, from which the final results arise. Since the importance of each shape systematic uncertainty can be better understood in terms of its effect on the final fitted discriminant, these uncertainties will be discussed in the next chapters. On the other hand, the sources of systematic uncertainties that have an impact on the normalisation of the respective background are common for all the background processes that are estimated in control regions.

The total normalisation systematic uncertainty consists of:

- the uncertainty that arises from higher-order terms in the perturbative QCD estimation that are not included in the Monte Carlo simulation that have been used. It is calculated by varying the renormalisation and factorisation scales by factors of 0.5 and 2.0;
- the uncertainty due to the chosen parton distribution functions (PDF) set. Each Monte Carlo generator uses a specific set of PDFs to simulate the generation of a particle. However, more than one PDF sets are available, and the choice of one over the others should be taken as a theoretical systematic uncertainty. The uncertainty due to the choice of PDF set is estimated by taking the largest difference between the chosen PDF set (e.g. CT10) and two alternative PDF sets (e.g. MSTW2008 [143] and NNPDF2.3 [144]), with the total uncertainty determined by the error eigenvectors of the chosen PDF set added in quadrature;
- the uncertainties that are due to the modelling of the underlying event (UE), the hadronisation process and the parton shower (PS), usually denoted as UE/PS. To evaluate these uncertainties, a comparison of the parton shower model that is used versus alternative models is taken into account.

5.4.2 WW Background Process

The dominant background process for the analyses presented in this thesis is the non-resonant W -boson pair production. The decay products from this background process are the same as for the signal process. Such processes are referred to as *irreducible*.

To separate between signal and irreducible W -boson pair background, only the kinematic properties of the event can be used. The normalisation of this background is performed in the control region, which is orthogonal to the signal one with respect to the range of the invariant mass distribution of the dilepton system, $m_{\ell\ell}$. The leptons produced from the background process, tend to have larger opening angles with respect to the resonant WW production, as described also in Chapter 1. In addition, the mass of the Higgs-boson is lower than the sum of the masses of the two W bosons in the non-resonant WW system. Therefore, the irreducible background process tends to have larger $m_{\ell\ell}$ values than the signal process.

Taking into account the differences in kinematical distributions between the signal and the background process, the control region for the 0-jet category is defined, after applying the dilepton p_T selection, by requiring an invariant mass for the dilepton system in the range of $80 < m_{\ell\ell} < 150$ GeV. Additionally, in the 1-jet category, the control region is defined after the m_T^ℓ selection, by requiring a $m_{\ell\ell} > 80$ GeV. In the 0-jet control region, the purity of the WW background process is estimated to be 69%, while in the 1-jet bin 43%. Due to the non-negligible presence of non- WW backgrounds in this control region, for the extraction of the WW normalisation factor, the normalisation factors from the Top and Drell-Yan control regions are applied to the respective backgrounds. Smaller backgrounds are estimated directly from simulation. Finally, the normalisation estimation is done globally, independently of the production process of the W -boson pairs (e.g. qq , gg or gq).

Figure 5.5 shows the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the WW control region for the 0- and 1-jet categories. In addition, the event yields for the signal and background processes in the WW control regions are given in Tables 5.6 and 5.7.

5.4.3 Top Background Process

The second largest background in the analyses is the top-quark background. The top-quarks can be produced either in pairs ($t\bar{t}$) or in association with a W boson (Wt) or lighter quark(s), a process called single-top production. As for the WW case, the background normalisation factor is calculated in a top background enriched control region and is performed globally, regardless of the production mode.

For the 0-jet bin, the control region is defined after the preselection requirements, including the missing transverse momentum threshold and an additional selection on the opening angle of the leptons, $\Delta\phi_{\ell\ell} < 2.8$, to reduce the $Z/\gamma^* \rightarrow \tau\tau$ background. For the 0-jet category the top CR is inclusive in the number of jets in the final state. The purity of the control region is estimated to be 74%.

As far as the 1-jet category is concerned, the top background is not only a leading background in the signal region, but in the WW control region as well. In fact, the contamination in the WW CR from the top-quark background is estimated to be about 40%. Due to this large contamination, two extrapolation factors are estimated: one for the extrapolation from the top control to the signal region, α_{SR} ; and one for the extrapolation from the top control region to the WW one, α_{WW} . The definition of the CR in the 1-jet category is performed after the preselection and requires the presence of exactly one b -tagged jet in the final state. The events with more than one b -tagged jets with transverse momenta in the range of $20 < p_T < 25$ GeV are vetoed. In addition, the requirements on the m_T^ℓ and $m_{\tau\tau}$ veto are applied.

Figure 5.6 shows the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the top control region for the 1-jet bin category. In addition, the event yields for the signal and

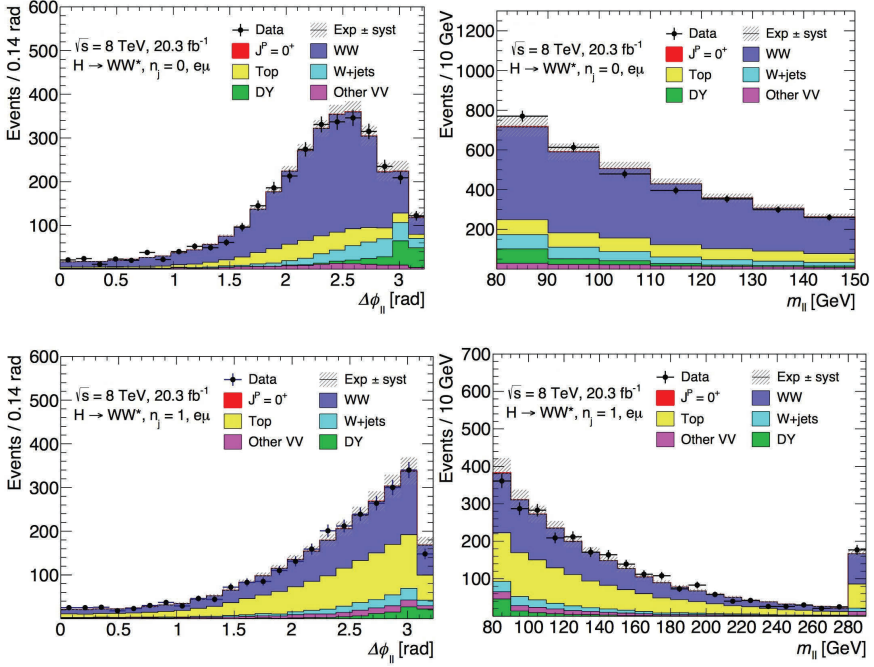


Figure 5.5: The $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the WW control region for the 0-jet (top) and the 1-jet (bottom) categories. The signal is assumed to be SM Higgs with $m_H = 125$ GeV. The contamination from the SM Higgs boson is less than 1% and is considered negligible. The normalisation factors for the Top and Drell-Yan background, as estimated in the respective control regions, are applied. The last bin in each plot includes overflow.

background processes in the top control regions are given in Tables 5.6 and 5.7.

5.4.4 Drell-Yan Background Process

The Drell-Yan background process consists of Z/γ^* bosons decaying either into $ee/\mu\mu$ or into a pair of τ -leptons. Due to the different flavour requirement, the Drell-Yan background process in the analysis mainly consists of the leptonic decays of the τ pair.

In the 0-jet bin the control region is defined after the preselection requirements, with the addition of the dilepton system invariant mass selection of $m_{\ell\ell} < 80$ GeV. The control region events are selected to have $\Delta\phi_{\ell\ell} > 2.8$, orthogonal to the SR requirements. The Z/γ^* background process purity in the control region is estimated to be 90%. Furthermore, in the 1-jet bin the

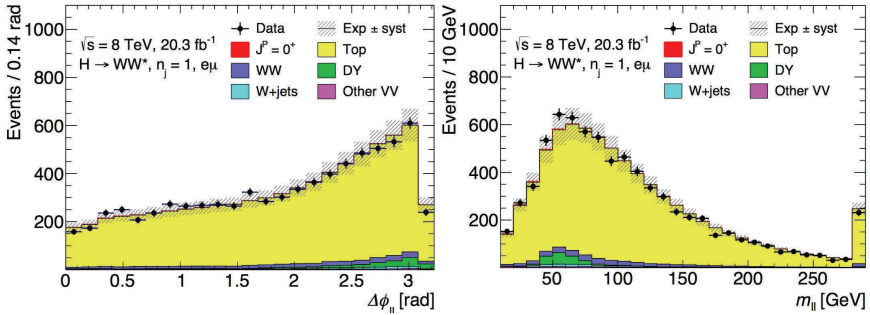


Figure 5.6: The $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the top-quark control region for the 1-jet category. The signal is assumed to be SM Higgs with $m_H = 125$ GeV. The contamination from the SM Higgs boson signal is less than 1% and is considered negligible. The normalisation factors for the WW and Drell-Yan background, as estimated in the respective control regions, are applied. The last bin in each plot includes overflow.

control region is defined after the preselection requirements, with in addition the b -veto and $m_T^\ell > 50$ GeV selection, but events are required to have $|m_{\tau\tau} - m_Z| < 25$ GeV. The process purity in the 1-jet CR is estimated to be about 80%.

As for the top background, two extrapolation factors are defined in the $Z/\gamma^* \rightarrow \tau\tau$ control region : one extrapolating from the control region to the signal region and one from the control region to the WW one, due to the 5% contamination of $Z/\gamma^* \rightarrow \tau\tau$ events in the WW control region.

Figure 5.7 shows the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the $Z/\gamma^* \rightarrow \tau\tau$ control region for the 0- and 1-jet bin categories. The transverse momentum of the Z boson, p_T^Z , which is reconstructed as $p_T^{\ell\ell}$, shows a mismodelling, which is more pronounced in the 0-jet bin category. The reason for this is attributed to the fact that the ALPGEN [145] + HERWIG [146] generator is not fully able to model the parton shower of the soft jets that balance the $p_T^{\ell\ell}$ in events with no selected jets. To correct for this, weights that are derived from data-to-MC comparison in the Z mass peak, are applied in bins of $p_T^{\ell\ell}$ in the 0-jet bin. These weights are applied to the p_T of the Z boson at generator-level. This procedure has an impact of 19% in terms of systematic uncertainty on the event yields in the signal region.

5.4.5 Misidentified Leptons

The last major background in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis is denoted as misidentified leptons. Its major component (85% – 90%) is the associated production of a W boson with an object which is misidentified as lepton. The

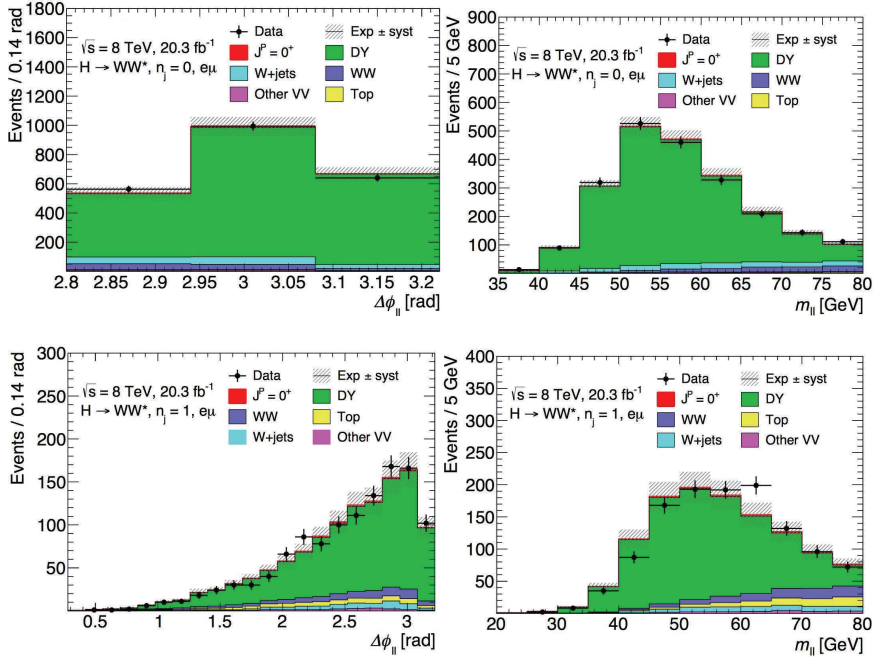


Figure 5.7: The $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions in the $Z/\gamma^* \rightarrow \tau\tau$ control region for the 0-jet (top) and the 1-jet (bottom) categories. The signal is assumed to be SM Higgs with $m_H = 125$ GeV. The contamination from the SM Higgs boson signal is less than 1% and is considered negligible. The normalisation factors for the WW and Top background, as estimated in the respective control regions, are applied. The last bin in each plot includes overflow.

misidentified lepton can either be a non-prompt lepton from hadron decays containing heavy quarks, or a particle that originates from a jet that is reconstructed as lepton candidate. The other component of the background is due to multi-jet production with two misidentified jets as leptons.

The estimation of this background process is data-driven using a specific $W + \text{jets}$ control sample. This sample consists of a pair of leptons, from which one lepton satisfies the identification and isolation criteria for the signal sample (referred to as *identified* lepton), while the other (referred to as "anti-identified") fails to satisfy these criteria, but successfully satisfies looser identification and isolation criteria. For anti-identified electrons, at least four hits in the SCT and Pixel detectors are required, while the $\frac{\sum E_T}{E_T}$ and $\frac{\sum p_T}{E_T}$ ratios selection is loosen. Similarly, for anti-identified muons, the requirement on the $\frac{\sum E_T}{p_T}$ ratio is loosen, while the requirement on the d_0 impact parameter is dropped, together with the removal of the track isolation requirements.

However, apart from the isolation and identification criteria, all events in the control sample should satisfy all the signal selection requirements.

The normalisation of this background in the signal region is obtained by scaling the number of events in the data control sample using an extrapolation factor. This extrapolation factor is obtained from another data derived control sample that contains $Z + \text{jets}$ events, where the Z boson has decayed in either the ee or the $\mu\mu$ final state. The factor, which is called *fake factor*, is the ratio of the identified leptons to the anti-identified ones, measured in bins of the anti-identified lepton p_T and η . Each number in the p_T and η bins includes correction for the presence of processes other than $Z + \text{jets}$ in the control sample (e.g. $WZ \rightarrow \ell\nu\ell\ell$ or Z/γ^*).

The different jet production mechanisms (heavy-flavour quarks, light-flavour quarks and gluons) vary in the $Z + \text{jets}$ and the $W + \text{jets}$ samples. Therefore, simulations are used to correct the extrapolation factors and to determine the associated uncertainty. For the simulations, a comparison of the extrapolation factors that are estimated for the $Z + \text{jets}$ and the $W + \text{jets}$ sample is performed using the ALPGEN+ PYTHIA6 [131], ALPGEN+ HERWIG and POWHEG [110] + PYTHIA8 [111] schemes. The ratio of extrapolation factors of $W + \text{jets}$ over $Z + \text{jets}$ is calculated per scheme and is used to determine the uncertainties. An additional uncertainty on the $Z + \text{jets}$ extrapolation factor is due to the limited statistics in the $Z + \text{jets}$ control that arise from the lepton selection criteria. For the multi-jet QCD background, the same procedure as for the $W + \text{jets}$ is performed twice.

The total systematic uncertainty on the extrapolation factors changes with the p_T of the anti-identified lepton [39]. The uncertainty is estimated in terms of p_T -bins ranging from 10 GeV to 25 GeV in steps of 5 GeV, with an additional bin containing anti-identified leptons with $p_T > 25$ GeV. For anti-identified electrons a variation from 29% (for $10 < p_T < 15$ GeV) to 61% (for $20 < p_T < 25$ GeV) is estimated, while for anti-identified muons the variation is estimated to be from 25% (for $10 < p_T < 15$ GeV) to 46% (for $p_T \geq 15$ GeV). This uncertainty is the dominant one for the $W + \text{jets}$ background process.

5.5 Signal Region Plots and Cutoffs

Tables 5.6 and 5.7 show the event yields for the signal and background processes, as well as the observed data events for the 2013 and 2014 analysis. Each row in the tables shows a different selection level in the signal region definition, starting for example from the requirement that the events have no associated jets in the final state, up to the $\Delta\phi_{\ell\ell} < 2.8$ requirement. The event yields also for the different control regions are shown. In addition, the pre-fit normalisation factors, derived from the control regions are quoted. From the last column, it is clear the excess of data on top of the background estimates, which is the result of the Higgs boson signal.

Finally, Figure 5.8 shows the distributions of four kinematic variables,

namely $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $p_T^{\ell\ell}$ and m_T , in the signal region for the 2013 analysis. The full selection criteria have been applied. Similarly Figures 5.9 and 5.10 show the same distributions for the 2014 analysis after the full selection criteria have been applied, for the 0-jet and 1-jet bin categories, respectively.

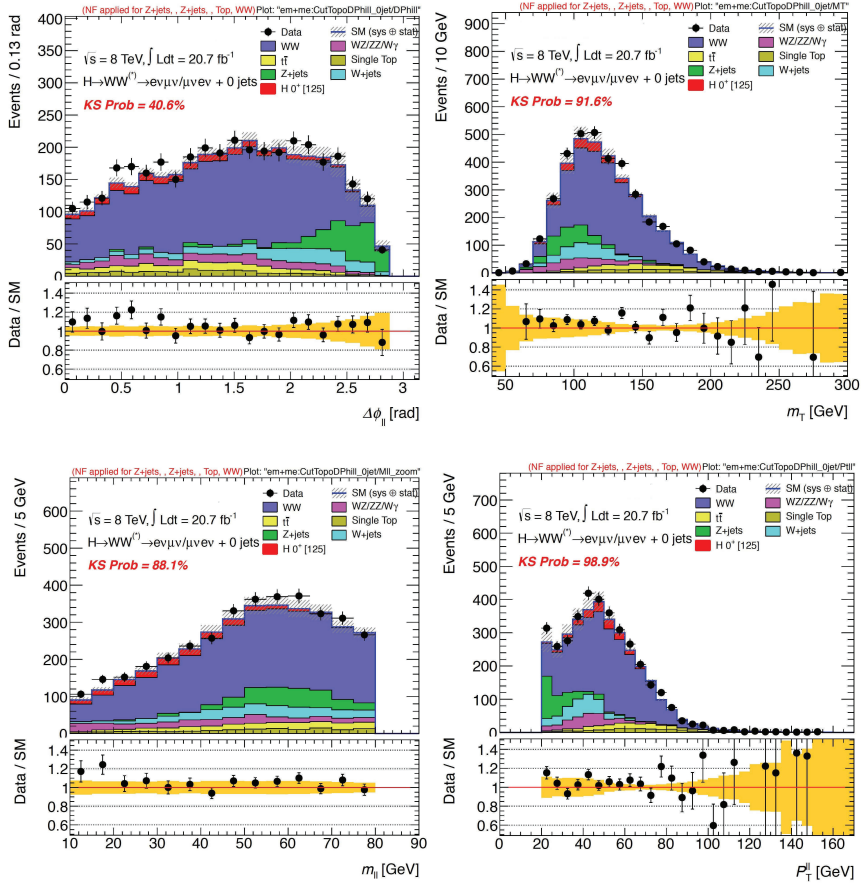


Figure 5.8: Expected and observed distributions of $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $p_T^{\ell\ell}$ and m_T distributions for the 0-jet category. The distributions are plotted in the signal region of the 2013 analysis. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson. The backgrounds are normalised using factors from the control regions.

	ggF [125 GeV]	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	Single Top	Z+jets	W+jets	Total Bkg.	Observed	Data/Bkg
Scale factors		NF = 1.08		NF = 1.05	NF = 1.05					
0j: Top control region	21.12 ± 0.56	379.17 ± 5.16	107.79 ± 15.81	28819.75 ± 59.87	2518.93 ± 21.05	269.70 ± 8.14	182.96 ± 5.36	32278.29 ± 66.32	33806	1.05 ± 0.01
Scale factors		NF = 1.08		NF = 1.07	NF = 1.07					
0j: jet veto	175.63 ± 1.50	5078.77 ± 18.57	421.01 ± 13.53	539.63 ± 8.28	329.57 ± 7.63	4181.31 ± 41.36	580.96 ± 8.39	11131.25 ± 49.35	11493	1.03 ± 0.01
0j: $p_{T,t\bar{t}} > 20$ GeV	170.14 ± 1.48	4622.63 ± 17.71	378.38 ± 12.63	514.89 ± 8.09	314.47 ± 7.46	667.02 ± 24.02	455.53 ± 6.58	6952.93 ± 34.65	7261	1.04 ± 0.01
0j: $m_{t\bar{t}} < 80$ GeV	169.60 ± 1.48	2212.68 ± 12.23	230.67 ± 8.78	178.35 ± 5.00	123.66 ± 4.63	610.19 ± 22.83	303.64 ± 5.62	3659.18 ± 28.73	3964	1.08 ± 0.02
0j: $\Delta\phi_{t\bar{t}} < 2.8$	168.16 ± 1.47	2190.39 ± 12.17	226.91 ± 8.76	176.12 ± 4.97	122.15 ± 4.61	291.05 ± 14.99	276.67 ± 4.62	3283.28 ± 22.73	3615	1.10 ± 0.02
0j: $Z \rightarrow \tau\tau$ control region	3.60 ± 0.21	95.31 ± 2.42	11.73 ± 1.22	5.09 ± 0.80	2.72 ± 0.69	3532.67 ± 37.48	94.57 ± 5.13	3742.09 ± 37.94	3474	0.93 ± 0.02
0j: WW control region	0.54 ± 0.09	2225.92 ± 11.83	147.71 ± 9.08	336.54 ± 6.36	190.82 ± 5.84	56.83 ± 7.49	151.89 ± 3.43	3109.71 ± 19.10	3297	1.06 ± 0.02

Table 5.6: Pre-fit outflow for signal and control regions for 0-jet selection of the 2013 analysis. Uncertainties are statistical only.

	ggF [125 GeV]	WW	WZ/ZZ/W γ	t $\bar{t}$	Single Top	Z $\rightarrow \ell\ell + \gamma$ /jets	Z $\rightarrow \tau\tau + \gamma$ /jets	W+jets	Total Bkg.	Observed	Data/Bkg
Scale factors		NF = 1.18		NF = 1.08	NF = 1.08		NFs applied		NFs applied		
0j: jet veto	228.78 $\pm$ 0.53	6439.65 $\pm$ 11.91	517.97 $\pm$ 7.28	769.05 $\pm$ 3.39	379.84 $\pm$ 1.94	84.28 $\pm$ 14.41	2843.93 $\pm$ 22.23	937.87 $\pm$ 8.01	117972.88 $\pm$ 31.24	1233	1.01 $\pm$ 0.01
0j: $p_T^{\text{jet}} > 20$ GeV	223.49 $\pm$ 0.52	6158.46 $\pm$ 11.65	492.67 $\pm$ 7.12	737.11 $\pm$ 3.32	366.73 $\pm$ 1.90	65.53 $\pm$ 10.76	1566.25 $\pm$ 16.43	802.38 $\pm$ 6.98	101919.13 $\pm$ 25.21	10338	1.01 $\pm$ 0.01
0j: $m_{\ell\ell} < 80$ GeV	222.37 $\pm$ 0.52	2860.80 $\pm$ 7.92	323.77 $\pm$ 5.91	240.43 $\pm$ 1.89	137.30 $\pm$ 1.26	45.39 $\pm$ 7.82	1402.30 $\pm$ 15.51	437.03 $\pm$ 5.63	5447.12 $\pm$ 20.89	5781	1.06 $\pm$ 0.01
0j: $\Delta\phi_{\ell\ell} < 2.8$	218.24 $\pm$ 0.52	2796.11 $\pm$ 7.83	311.35 $\pm$ 5.81	235.38 $\pm$ 1.87	134.89 $\pm$ 1.22	31.65 $\pm$ 4.80	514.79 $\pm$ 9.08	365.62 $\pm$ 4.85	4389.79 $\pm$ 15.13	4730	1.08 $\pm$ 0.02
0j: $\text{HPt} < 125$ GeV	218.24 $\pm$ 0.52	2796.11 $\pm$ 7.83	311.35 $\pm$ 5.81	235.38 $\pm$ 1.87	134.89 $\pm$ 1.22	31.65 $\pm$ 4.80	514.79 $\pm$ 9.08	365.62 $\pm$ 4.85	4389.79 $\pm$ 15.13	4729	1.08 $\pm$ 0.02
0j: $\text{HPt} < 300$ GeV	218.24 $\pm$ 0.52	2796.11 $\pm$ 7.83	311.35 $\pm$ 5.81	235.38 $\pm$ 1.87	134.89 $\pm$ 1.22	31.65 $\pm$ 4.80	514.79 $\pm$ 9.08	365.62 $\pm$ 4.85	4389.79 $\pm$ 15.13	4730	1.08 $\pm$ 0.02
Scale factors		NF = 1.26	18.23 $\pm$ 1.32	8.91 $\pm$ 0.35	3.97 $\pm$ 0.28	15.69 $\pm$ 6.20	1921.22 $\pm$ 18.50	128.23 $\pm$ 4.08	2182.40 $\pm$ 20.02	2198	1.01 $\pm$ 0.02
0j: Z $\rightarrow \tau\tau$ control region	6.13 $\pm$ 0.09	NF = 1.18		NF = 1.08	NF = 1.08		NFs applied		NFs applied		
Scale factors		NF = 1.18		NF = 1.08	NF = 1.08		NFs applied		NFs applied		
0j: WW control region	1.12 $\pm$ 0.04	2183.56 $\pm$ 6.96	116.47 $\pm$ 3.31	285.97 $\pm$ 2.07	143.06 $\pm$ 1.18	14.03 $\pm$ 5.94	140.51 $\pm$ 4.94	277.84 $\pm$ 3.68	3161.48 $\pm$ 11.76	3170	1.00 $\pm$ 0.02
Scale factors		NF = 1.07		NF = 1.03	NF = 1.03		NFs applied		NFs applied		
1j: one jet	108.30 $\pm$ 0.33	2645.39 $\pm$ 7.24	425.58 $\pm$ 6.10	7672.50 $\pm$ 10.47	2106.34 $\pm$ 4.17	59.06 $\pm$ 13.37	4207.37 $\pm$ 24.74	720.52 $\pm$ 8.41	17836.76 $\pm$ 32.83	17888	1.00 $\pm$ 0.01
1j: b-jet veto	94.37 $\pm$ 0.31	2310.54 $\pm$ 6.72	360.61 $\pm$ 5.63	1473.45 $\pm$ 4.56	504.17 $\pm$ 2.20	49.60 $\pm$ 12.36	3604.75 $\pm$ 22.90	580.59 $\pm$ 7.34	8943.72 $\pm$ 25.87	8947	1.00 $\pm$ 0.01
1j: Z $\rightarrow \tau\tau$ veto	80.60 $\pm$ 0.29	1597.37 $\pm$ 5.59	233.71 $\pm$ 4.59	1005.00 $\pm$ 3.76	353.78 $\pm$ 1.84	18.84 $\pm$ 5.28	548.53 $\pm$ 9.45	236.59 $\pm$ 4.12	3993.84 $\pm$ 14.28	4067	1.04 $\pm$ 0.02
1j: $m_{\ell\ell} < 80$ GeV	80.34 $\pm$ 0.29	805.09 $\pm$ 3.96	152.24 $\pm$ 3.83	465.47 $\pm$ 2.56	174.94 $\pm$ 1.37	12.11 $\pm$ 3.64	525.98 $\pm$ 9.24	145.47 $\pm$ 3.53	2281.30 $\pm$ 12.24	2370	1.04 $\pm$ 0.02
1j: $\Delta\phi_{\ell\ell} < 2.8$	78.34 $\pm$ 0.28	767.97 $\pm$ 3.87	145.03 $\pm$ 3.73	451.15 $\pm$ 2.52	169.27 $\pm$ 1.31	6.18 $\pm$ 1.06	228.00 $\pm$ 5.95	127.89 $\pm$ 3.16	1895.49 $\pm$ 9.13	2014	1.06 $\pm$ 0.02
1j: $m_T \leq 1.2 \cdot m_H$	76.63 $\pm$ 0.28	554.82 $\pm$ 3.28	131.41 $\pm$ 3.60	267.23 $\pm$ 1.94	103.39 $\pm$ 1.12	5.75 $\pm$ 1.02	227.71 $\pm$ 5.95	122.88 $\pm$ 3.08	1413.19 $\pm$ 8.64	1569	1.11 $\pm$ 0.03
1j: $\text{HPt} < 125$ GeV	75.33 $\pm$ 0.28	529.72 $\pm$ 3.21	127.68 $\pm$ 3.55	258.73 $\pm$ 1.91	100.75 $\pm$ 1.10	5.75 $\pm$ 1.02	223.52 $\pm$ 5.89	121.26 $\pm$ 3.06	1367.41 $\pm$ 8.54	1511	1.11 $\pm$ 0.03
1j: $\text{HPt} < 300$ GeV	76.60 $\pm$ 0.28	553.41 $\pm$ 3.28	131.35 $\pm$ 3.60	266.98 $\pm$ 1.94	103.32 $\pm$ 1.12	5.75 $\pm$ 1.02	227.71 $\pm$ 5.95	122.79 $\pm$ 3.08	1411.31 $\pm$ 8.64	1567	1.11 $\pm$ 0.03
Scale factors		NF = 1.25	20.69 $\pm$ 1.30	47.64 $\pm$ 0.81	15.58 $\pm$ 0.47	5.44 $\pm$ 3.32	940.93 $\pm$ 11.55	54.12 $\pm$ 2.69	1169.82 $\pm$ 12.49	1184	1.01 $\pm$ 0.03
1j: Z $\rightarrow \tau\tau$ control region	4.80 $\pm$ 0.07	NF = 1.07		NF = 1.03	NF = 1.03		NFs applied		NFs applied		
Scale factors		NF = 1.07		NF = 1.03	NF = 1.03		NFs applied		NFs applied		
1j: WW control region	0.41 $\pm$ 0.02	1170.46 $\pm$ 4.80	130.40 $\pm$ 3.22	808.29 $\pm$ 3.37	201.98 $\pm$ 1.50	16.60 $\pm$ 8.65	81.22 $\pm$ 3.31	171.89 $\pm$ 3.02	2640.85 $\pm$ 11.98	2647	1.00 $\pm$ 0.02
Scale factors		NF = 1.07		NF = 1.03	NF = 1.03		NFs applied		NFs applied		
1j: Top control region	12.17 $\pm$ 0.12	292.01 $\pm$ 2.51	54.02 $\pm$ 2.15	5451.74 $\pm$ 8.85	1399.38 $\pm$ 3.30	3.88 $\pm$ 1.86	150.41 $\pm$ 5.17	88.12 $\pm$ 3.25	7439.55 $\pm$ 11.87	7422	1.00 $\pm$ 0.01

Table 5.7: Pre-fit cutflow for signal and control regions for 0- and 1-jet selections of the 2014 analysis. Uncertainties are statistical only.

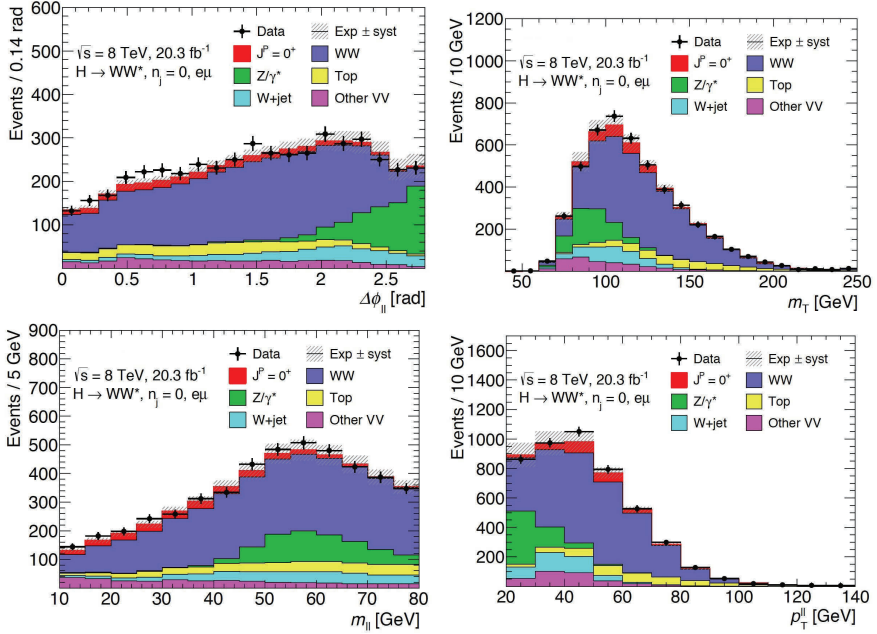


Figure 5.9: Expected and observed distributions of $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $p_T^{\ell\ell}$ and m_T distributions for the 0-jet category. The distributions are plotted in the signal region of the 2014 analysis. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson. The backgrounds are normalised using factors from the control regions.

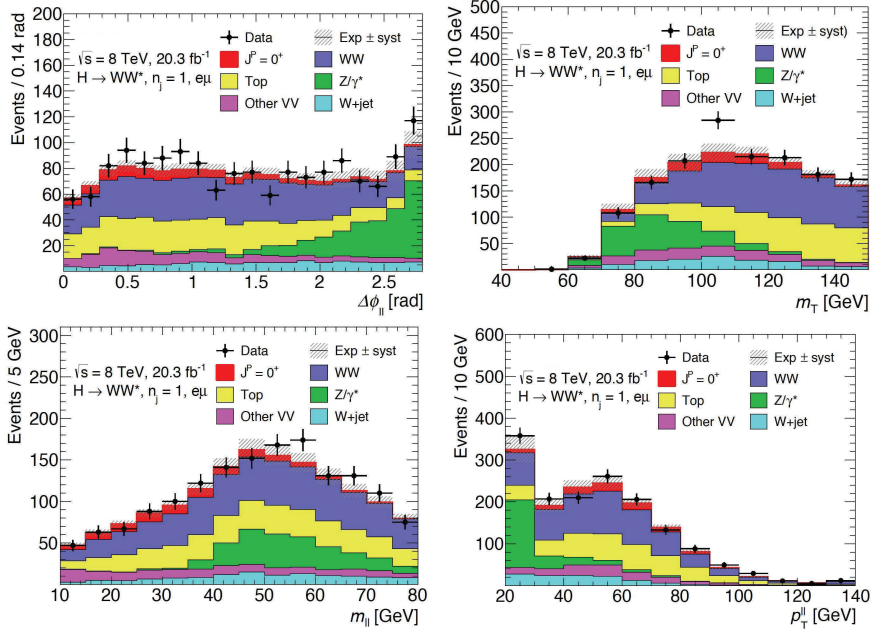


Figure 5.10: Expected and observed distributions of $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $p_T^{\ell\ell}$ and m_T distributions for the 1-jet category. The distributions are plotted in the signal region of the 2014 analysis. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson. The backgrounds are normalised using factors from the control regions.

Evidence of the Spin-0 Nature of the Higgs boson

This chapter discusses the 2013 $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ spin analysis [120] performed on the $\sqrt{s} = TeV$ data-set, with $20.7fb^{-1}$ in total. The signal and background modelling, as well as the definitions for the signal and control regions have been presented in the previous chapters.

The analysis focuses on testing the SM spin and CP hypothesis of the Higgs boson, comparing it to the alternative models with spin- $1^\pm$ and spin- 2^+ . The design of the analysis and the various steps and optimisations that took place are presented in the next section. Then the treatment of the systematic uncertainties and the statistical interpretation of the analysis is presented. Finally, the results of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis are presented.

The results of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis were combined with the ones from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels [119]. The combined results are discussed at the end of this chapter.

6.1 Defining the Analysis Strategy

This section will give a description of the procedure that was followed to specify the strategy for the analysis. The analysis is based on Boosted Decision Trees implemented in the TMVA [74] package. A short description of the method procedure and its features are described. Then the procedure for optimising the training phase of the method will be presented and will be the basis for the studies on the optimisation of the method that is finally used for the results.

6.1.1 Blinding the Analysis

To study the performance of the analysis without biasing the procedure towards the result, the procedure referred to as *blinding* is applied. The blinding procedure takes into account the phase space region where the expected signal should be and "hides" this region from all the data (mainly), as well as from the simulated samples. This hiding procedure is applied by requiring certain selection criteria to be applied before the study is performed on the samples. These criteria are defined in such a way that the signal contamination outside of the blinded region is minimal. After the blinding procedure is done, the design of the analysis can start, without any bias towards the signal, and the results are expressed in terms of the expected sensitivity. The blinding procedure is especially important in excess searches, where the collected observed data are forming an excess of events when compared to background-only hypothesis of simulated samples.

The blinding criteria are applied in logical AND. The criteria used for this analysis are defined in a way so that the alternative signal hypotheses are also blinded, since they manifest themselves in a slightly different kinematic regime with respect to the SM hypothesis. Therefore, the requirements that are applied are

$$m_T < 140 \text{ GeV} \ \&\& \ m_{\ell\ell} < 80 \text{ GeV} \ \&\& \ \Delta\phi_{\ell\ell} < 2.8.$$

The requirement on m_T alone removes almost 95% of the signal events independent of the spin hypothesis, and the selection on $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ are needed to define the WW and Z/γ^* control regions. In the following tables and figures, when the signal region is blinded it will be mentioned explicitly.

6.1.2 Short Description of the BDT Method

The analysis presented in this chapter is a shape-based analysis fully exploiting the features of the *Boosted Decision Trees* multivariate method. With respect to a conventional cut-and-count technique, the multivariate approach is advantageous in defining the region where the signal **should** be, the signal region. In a cut-and-count method the signal region is defined by orthogonal selections of kinematic and topological distributions. This usually minimises the available phase space in order to increase the signal over background events ratio (usually referred to as *significance*) and assumes that most of the events in the remaining rectangular shaped signal region correspond to the signal process. On the other hand, in multivariate methods the signal region is defined to be broader. Through multiple iterations of running the method a weighted output is generated which gives a probability of each event to be signal, or background. In this frame, the signal region is shaped as a multi-dimensional space driven by a "probability density function" which associates each event that falls within the signal region with a weight (i.e. a probability) to be a

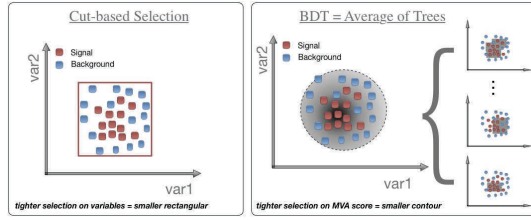
signal or a background event. Figure 6.1a shows a schematic of the difference in principle between the two approaches, as well as the corresponding determination of the signal region.

In the case of Boosted Decision Trees, the method simply consists of a collection of selection requirements that are used to classify events as signal or background. The method proceeds in two phases: the *training phase* and the *classification phase*. For illustration purposes, a simple analysis under study could be assumed to be where there is one signal sample and one background sample. From each of these samples two samples that are randomly selected subsets of the original one are selected: one is referred to as the *training sample* and one as the *test sample* of the given process.

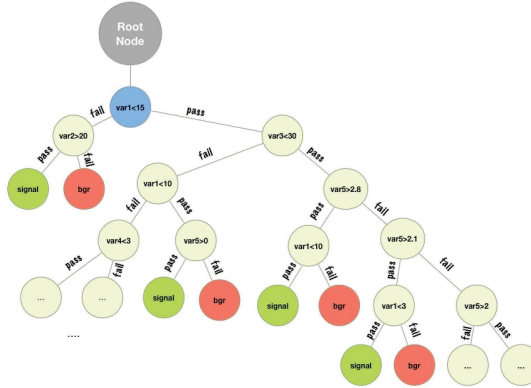
The training phase is seeded with the two training samples which are *a priori* known to be signal and background ones. In addition, the method is seeded with a selection of kinematic distributions, usually referred to as *input variables*. These are the distributions that the method will identify in the input samples comparing their shapes, as well as the linear and non-linear correlations between them. At this point a decision tree is starting to show. From the total collection of events provided in the training sample, the method, based on the knowledge acquired from the input variables, splits the initial collection of events (usually referred to as *Root Node*) into two collections (i.e *nodes*), one signal-like and one background-like, depending on the pass-fail fulfilment of a certain requirement on an input variable. This procedure continues until the stopping requirements are met. The stopping requirements are settings of the method. The two main ones are the maximum number of steps that the tree can develop, referred to as *MaxDepth*, and the minimum number of events that should be in one of the terminal nodes, referred to as *nMinEvents*. In this step, the tree consists of final nodes that contain predominantly signal or background events. A given signal event is correctly identified when it is in a signal-dominated node.

At this point a new tree starts to develop from scratch targeted to identify events that were misclassified in the first tree. Misclassified events are assigned an increased weight or *boost*, which is relative to the correctly-classified events. This procedure of generating trees continues iteratively until a predefined number of trees is reached, referred to as *nTrees*.

Finally, all the weights collected using the training phase are used during the *classification phase*. During the classification phase, the trained method is applied to the test data-set and provides scalar outputs according to which event is considered to be signal or background. The weighted average of these outputs forms the BDT output discriminant. The BDT output is a distribution ranging from -1 to 1 , with the region towards -1 referred to as background-like region and the one towards 1 referred to as signal-like region.



(a)



(b)

Figure 6.1: (a) Comparison of the principles following a cut-based analysis and a multivariate one, specifically a Boosted Decision Tree, in a simple case with two discriminating variables. (b) The sequential decision-making procedure of the BDT method. Starting from a Root Node, the events are split in signal-like and background-like events depending on if they pass or fail a certain requirement on an input variable. The splitting of the events in each node creates the tree-shaped structure that is shown, hence the name of the method. The procedure continues iteratively, building more trees, until the stopping criteria are met.

6.1.3 Designing the Training Phase

Designing and optimising a multivariate method can be quite time-consuming, but the end result in most cases is advantageous to the conventional cut-based searches. Specifically, the Boosted Decision Trees method is very powerful in identifying shape variations on the input variables between the signal and the background processes. This allows the method to find an optimal cut on a variable that best separates the two. On top of that, the method can exploit in full the non-linear correlation schemes between the input variables and identify the best separating ones that are to be used in the first selection node. Input variables that are either not very powerful in terms of separation

power or highly correlated with more separating ones can also be included in the training without saturating the performance of the method, with the only expense being CPU time.

On the negative side, the BDT during the training phase suffers when the statistics of the training samples are too low. This induces *overtraining*. Overtraining (or over-fitting) is a common issue among artificial learning machines. It arises when the degrees of freedom of the machine learning problem are too few, due to too a large number of model parameters of the algorithm are adjusted to few data points. For example, during the training phase, if the training samples have low statistics the shapes of the input variables are prone to large fluctuations. However, since the machine is trained on these variables, it learns that it should look for the respective statistics-induced fluctuations in the testing sample, which is not desirable. Specifically, apart from the low sample statistics, BDTs suffer from partial overtraining if not configured properly in terms of the number of nodes.

The first step towards designing a training for a BDT is to define the signal and background processes that will be used in the training phase and their respective signal region. In the simple case, where there is only one signal and few background processes this step is clear. The statistics of the training sample should be sufficient for the training such that overtraining issues are avoided. This is also partly driven from the selection requirements that are applied on the training samples. These requirements are fulfilled before the actual training starts and are targeted to remove already known background-populated regions so that the machine does not take these regions into account while being trained.

The next crucial step is the selection of discriminating variables to be used as input variables for the method. Since the method uses these to separate signal from background events identifying their shape and correlation schemes, they have to contribute to the separating power. Therefore, sets of highly correlated variables and variables with no separating power should be avoided. When the training phase ends, the training algorithm derives a *ranking of the input variables* by counting how many times a given variable is used to split a node, weighted by the number of events in the node and the gain in signal-background separation. Therefore, when selecting the input variables usually the so-called $N-1$ optimisation method is used. Starting from a pool of candidate input variables that show that they have a separating power in terms of shapes, a training is applied using all of them as inputs. When the training is finished the ranking table is studied along with the curve of background rejection as a function of signal efficiency (usually referred to as *Receiver-Operating-Characteristic* (ROC) curve). The ROC curve shows the overall performance of the method in terms of background rejection. By looking at the ranking and the correlations between the variables, low ranked variables are removed and the training is performed again. A new ranking table and a ROC curve are done. Comparing the performance of two trainings, by calculating the area under the curve (AUC), a decision can be made whether the variable

removed was adding separation power or not. This procedure continues in an iterative way until no more variables can be removed from the input ones without a performance drop.

Figure 6.2 shows an example of a comparison performed on the ROC curves of five different trainings for the training of SM Higgs signal process against all the SM background processes at the 0-jet category. Starting from a collection of seven input variables and keeping the same settings for the training, in each step some variables are removed. When removing a non-separating variable as for example the pseudorapidity of the leading lepton, $\eta^{\ell 1}$, the performance of the method remains the same. This is already an indication that this variable does not help in the separation power of the method, but including it the performance does not saturate. Next, removing the $\Delta\phi_{\ell\ell}$ the performance of the method stays roughly the same, due to the fact that $\Delta\phi_{\ell\ell}$ is highly correlated with $m_{\ell\ell}$ which is still used. However, this is not the case in the fourth training, when both $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ variables are removed. A drop in the performance is shown. Finally, to illustrate the handling of the correlations between the input variables from the Decision Tree, a final training was performed using only the transverse momentum of the dilepton and the invariant transverse mass of the event. These two variables are in principle powerful enough in the cut-based regime to separate the Higgs signal from the background processes. However, a large drop of the performance is shown when removing the information of the variables that show different correlation schemes between the signal and the background samples.

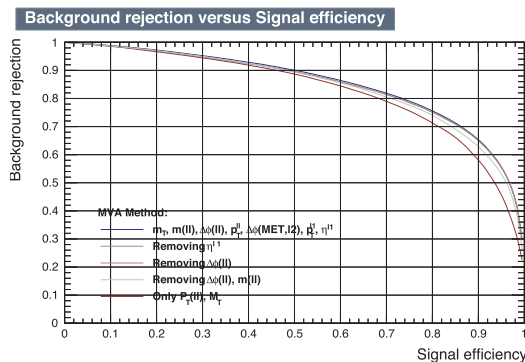


Figure 6.2: An example of using the ROC curves as a mean to optimise the selection of input variables in the training phase. Five trainings are performed, one using all the information and the others subsequently removing input variables from the method.

The aforementioned steps are the most basics in designing the training phase. Additional fine-tuning is required to optimise the size of each decision tree and the total number of trees. The fine-tuning per tree is performed by

selecting the appropriate settings for number of levels the decision tree will progress, which is defined in TMVA as *MaxDepth*, and the minimum number of events a terminal node is required to have, defined as *nMinEvents*. Both these two settings, when combined with the number of trees (*NTrees*) the machine should develop, have an impact on the overtraining of the method. In order to detect if the machine suffers from overtraining and measure its impact, a comparison of the resulting discriminant is performed in the training and testing samples. To quantify the effect of overtraining a Kolmogorov-Smirnoff [147, 148] test is applied for the shapes of signal and background distributions, between the training and testing samples.

6.1.4 Design of the Spin/CP Analysis Strategy

The case of the spin analysis in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay mode is more complicated in terms of the training phase, compared to what has been discussed up to now. In this analysis, the background processes are known and Monte Carlo simulated samples are available to use, but the problem arises when taking into account the signal. Since the study focuses on separating between different spin hypotheses, the BDT training does not contain only one signal process. Therefore, the analysis has to be designed in a way that the background processes are well separated with respect to the signal ones, and in the meantime be able to provide a BDT discriminant that separates the two signal hypotheses.

Several approaches have been studied in order to achieve this goal. A brief description of them follows, for the purpose of completeness:

- Perform a BDT training where both spin-0 and spin-2 are the signal and all background processes are the background training samples. A selection would be applied on the BDT discriminant to remove background events. Then the final result would come from a fit to a spin-sensitive variable. A spin-sensitive variable is defined as one that presents significant differences in the shapes for the different signal hypotheses.

For this training, non-spin-sensitive variables are used. In detail, the variables used are the invariant transverse mass of the event, the transverse momenta and η of both the leading and sub-leading leptons, as well as the difference $\Delta\eta^{\ell\ell}$ of the two leptons. Figure 6.3a shows the BDT output discriminant of such a strategy. The two signal hypotheses are shown in dashed lines, while the background processes are stacked. The two dashed lines that were the signal in the training phase peak towards the +1 region of the BDT output. However, it seems from the shapes that a BDT trained in this way cannot separate between spin-2 signal and some of the background processes (e.g. $W + \text{jets}$ background).

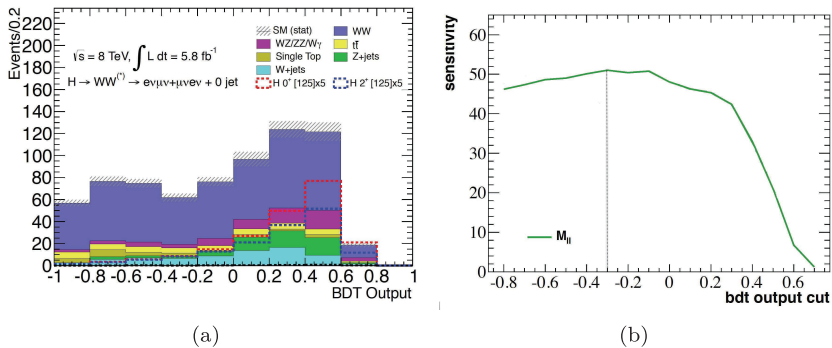


Figure 6.3: (a) The BDT score for the analysis strategy that combines both spin-0 and spin-2 signals to be trained versus the SM background processes. The spin-0 (red dashed) and spin-2 (blue-dashed) signals are scaled by a factor of 5. The background processes are stacked. (b) A scan on the sensitivity of the method as a function of the minimum selection value of the BDT score. The sensitivity is taken performing a fit on the $m_{\ell\ell}$ distribution.

A study on the sensitivity¹ on fitting a spin-sensitive variable is shown in Figure 6.3b. The fit is performed on the invariant mass of the dilepton system and the optimal range of the BDT output was for events that have a score larger than -0.3 . Therefore, the final result was taken by fitting the $m_{\ell\ell}$ distribution after a selection of $\text{BDTScore} > -0.3$.

This analysis strategy was not optimal for the spin-2 hypothesis, due to the similarities of the spin-2 signal with the SM background processes. In addition, since these background processes were defined as background sample for the method, the analysis would be slightly biased towards the spin-0 hypothesis. The BDT score is mainly driven from the separation of the spin-0 signal against the SM background processes, and its shape is slightly diluted from the behaviour of the spin-2 signal kinematics. However, under the assumption that the observed resonance has spin-2, this strategy is proved to be not strong in separating it from the SM background processes. To remove such constraints a new analysis strategy was designed.

- Perform a BDT training where spin-0 is the signal and spin-2 is the background training sample, no background processes considered in the

¹The definition of the sensitivity in this plot is different from what will be presented later on in Section 6.6. A log likelihood is defined as $LL = \log \text{Poisson}(N(x), N_{sig}(x) + N_{bkg}(x)) + \mathcal{A}_{constraint}$, where N_{sig} and N_{bkg} correspond to the number of signal and background events, respectively. Computing the difference in log-likelihood for a spin-2 event fraction of 1 with the minimum of the log-likelihood provides a distribution. The sensitivity is defined here as the median of this distribution. This was a preliminary statistical interpretation tool used until the framework that exploits the procedure described in Section 6.6 was developed.

training. The final result would arise from a fit to the BDT discriminant. This analysis strategy focuses on using the shapes of spin-sensitive variables to separate the two signal hypotheses, without the constrain of the shapes of the background processes. The spin-sensitive variables used are the invariant mass of the dilepton system, as well as the transverse momentum, azimuthal angle and pseudorapidity of each lepton. Due to the small number of available objects in the 0-jet category, most of the variables are highly correlated.

Figure 6.4 shows the BDT score for this training when the spin-0 is used as signal (Figure 6.4a) and when spin-2 is used as signal in the training (Figure 6.4b). The method is applied on all background processes as well. The two scores are symmetric as far as the signal shapes are concerned. However, since the training was done without using the information of any SM background process, the testing of the method on these processes fail to assess them as either signal or background, and the BDT score takes values around 0. When fitting the BDT score from this method, a decrease of about -20% was found in the separation of the two signals with respect to the previous strategy. Therefore, this analysis strategy was dropped.

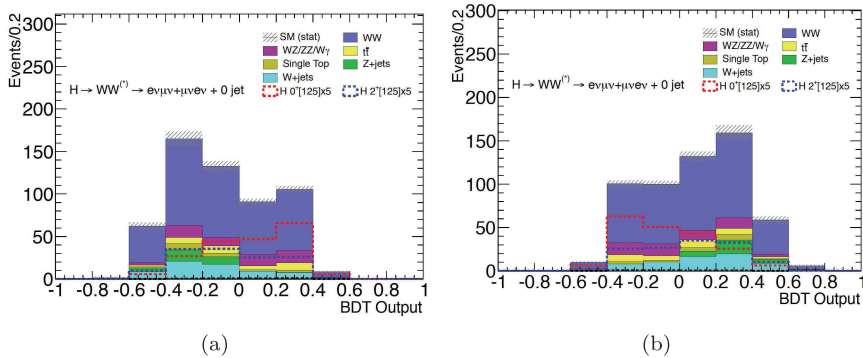


Figure 6.4: The BDT scores for the Signal versus alternative Signal training. In (a) the spin-0 hypothesis is used as signal and the spin-2 as background, while in (b) is the other way around. The spin-0 (red dashed) and spin-2 (blue-dashed) signals are scaled by a factor of 5. The background processes are stacked. The score is around 0 since the method is not trained on any SM background process.

6.1.4.1 Final Analysis Strategy

Based on the knowledge gained from testing the previous strategies the final one was derived and proved to be the best performing one. Since, both the signals (spin-0 and spin-2) have to be separated from the background processes, but in the meantime the method has to be able to separate between

the two spin-hypotheses, two BDT methods are trained. The first BDT, referred to as BDT0 onwards, is trained to separate the spin-0 signal from all the background processes. The second one, referred to as BDT2 onwards, is trained to separate the spin-2 signal from the background processes. With this configuration, each BDT can separate one signal hypothesis from all the background processes. This configuration gives the maximum separation between the Higgs signal, without taking into account its spin hypothesis, from all the background processes. This is especially powerful, for the spin-2 signal whose kinematics are similar to some of the background processes.

The variables used for the training are the invariant mass, the difference in azimuthal angle and the transverse momentum of the dilepton system, as well as the invariant transverse mass of the whole event. For each training, the scheme is similar to the BDT method that was used for the observation studies in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel [149]. The shapes of the input variables after applying the $E_{T,\text{rel}}^{\text{miss}}$ and $p_T^{\ell\ell}$ requirements are shown in Figure 6.5. Both signal hypotheses are shown together with all the background ones. Comparing the shapes of the two signal hypothesis for each variable already gives a hint on the separation power that the respective variable provides in the BDT. Table 6.1 shows the ranking of the input variables, which is the same for both the BDT0 and BDT2. In addition, Figure 6.6 shows the linear correlations between the variables in the spin-0, spin-2 signals, as well as in the background processes. The shape distributions of the BDT discriminant are shown in Figure 6.7. The plots include the Monte Carlo simulated signal and background samples and are normalised to unit area.

Variable	spin 0	spin 2
$m_{\ell\ell}$	1	1
$\Delta\phi_{\ell\ell}$	2	2
m_T	3	3
$p_T^{\ell\ell}$	4	4

Table 6.1: Ranking of BDT training variables in the $e\mu+\mu e$ and 0 jet final state.

However, the method up to now is only able to separate Higgs-like signal from other SM background processes. For the separation between the two signal hypotheses, the shape and correlations of the two signals with respect to the background processes were exploited. To achieve this, the two BDT scores are combined in a two dimensional space. Figure 6.8 shows the two-dimensional map of the two BDT outputs for the spin-0, the spin-2 signal and the background processes. The signals have a score around the positive values of the two BDTs, therefore in the two-dimensional space, their distributions would peak at the top right corner. Similarly, the background processes would peak at the bottom left corner. This provides the separation of the two

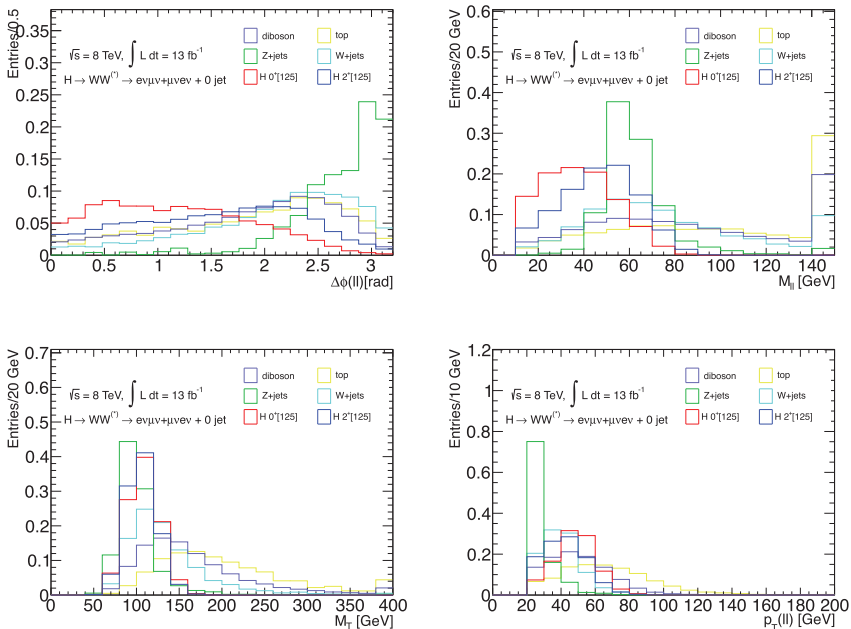


Figure 6.5: The shapes of input variables - $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_T , $p_T^{\ell\ell}$ for both signal hypotheses (dashed line) and backgrounds (solid line) after $E_{T,\text{rel}}^{\text{miss}}$ and $p_T^{\ell\ell}$ cuts.

signals from the SM background processes. On top of that, the correlations and shapes of the two signals are different, when trained with respect to the SM background processes. This comes from the fact that the spin-2 signal, when trained against the background processes, results in a slightly different configuration in the two-dimensional BDT0×BDT2 space, since its shape is very similar to some of the backgrounds (mainly $W + \text{jets}$ and WW). Thus, the BDT scores in the two-dimensional space have different distributions, as shown also in the Figure 6.8. This provides the separation between the two signal hypotheses.

For the final result, the BDT0×BDT2 space, binned by 10×10 bins is unrolled in an one-dimensional distribution row-by-row. This one-dimensional distribution is used for the final statistical treatment.

6.2 Optimisation of the Analysis

Now that the analysis strategy is defined, its refinement is performed. The definition of training and testing samples, the signal region definition at the training and testing phase, as well as the training parameters for the decision

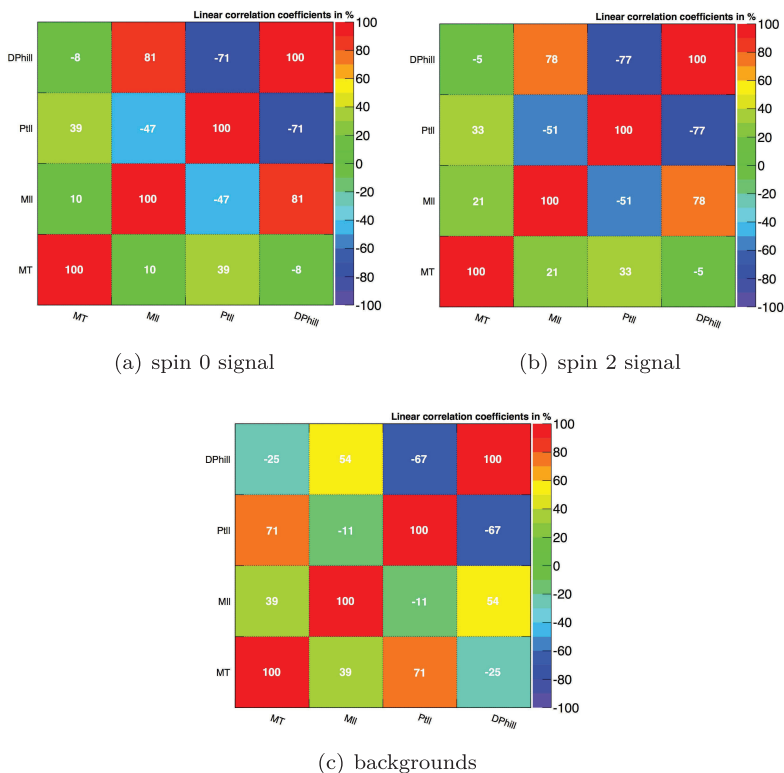


Figure 6.6: Linear correlation coefficients among MVA discriminant variables in the 0-jet $e\mu$ final state for a 125 GeV (a) spin 0 signal, (b) a spin 2 signal and (c) the backgrounds.

tree and the training schemes for the different spin-2 production mechanisms are discussed in the following.

6.2.1 Training and Testing Sample

To successfully perform a study using a BDT two independent collection of events must be selected: one to train the method and one to test it. The statistics of the available Monte Carlo simulated samples were sufficient to train a BDT without inducing overtraining for all signal and background processes. Therefore, to create the two samples, each simulated process is split in half. To pseudo-randomise this split, from each initial sample, events with even entries in it are chosen to be the training sample, while the odd ones are selected to be the test sample.

This split sample configuration may arise concerns, mainly due to the avail-

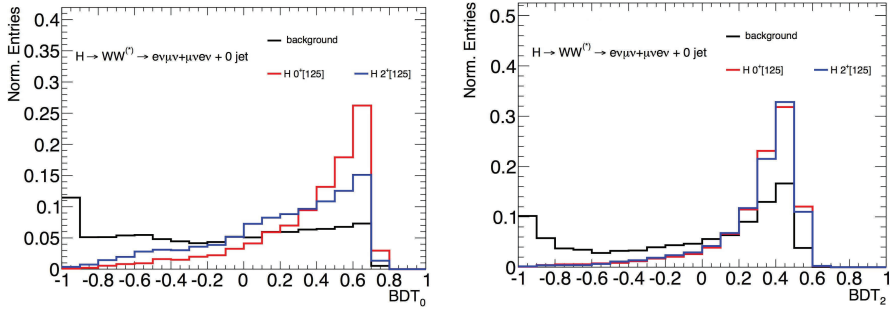


Figure 6.7: Monte Carlo BDT spin-0 and spin-2 shape distributions in the signal region.

able statistics, in the case of the $Z/\gamma^* + \text{jets}$ background sample, which has with respect to other samples slightly less events. To alleviate such concerns, one could remove these two samples from the training phase and only use them in the testing phase. However, removing two of the major backgrounds from the training phase would result in a dropped performance overall.

To solve this issue, each of the BDT0 and BDT2 trainings are performed twice: once using the *Even* sample and once using the *Odd* one. Finally, when testing the method, the weights extracted from the Even training are tested on the *Odd* sample and vice-versa. This technical trick, allows for the use of the full sample as test sample, while maintaining completely independent training and testing sample configuration. This is a technical improvement of the method compared to the one described in Ref. [149]. In addition a check had also been performed in including or removing the $Z + \text{jets}$ sample from the training phase. The results show that the background process can be included in the training without a negative impact on the method. On the contrary, the overall performance is increased. The results are summarised in Table 6.2.

6.2.2 Event Selection Before and After the Training

An optimisation on the selection requirements after the $E_{T,\text{rel}}^{\text{miss}}$ preselection criteria in terms of which are to be applied before the training phase and which after the training phase of the method have been performed. A scan over the various configurations on selection requirements in the training and the testing phase is shown in Table 6.2. The variables used in the signal region definition are applied either before, or after the training phase and the expected sensitivity in terms of Z values for the two signal hypotheses is used to identify their performance.

The best performing configuration proved to be the use of the signal region definition both in the training and in the testing phase. However, the

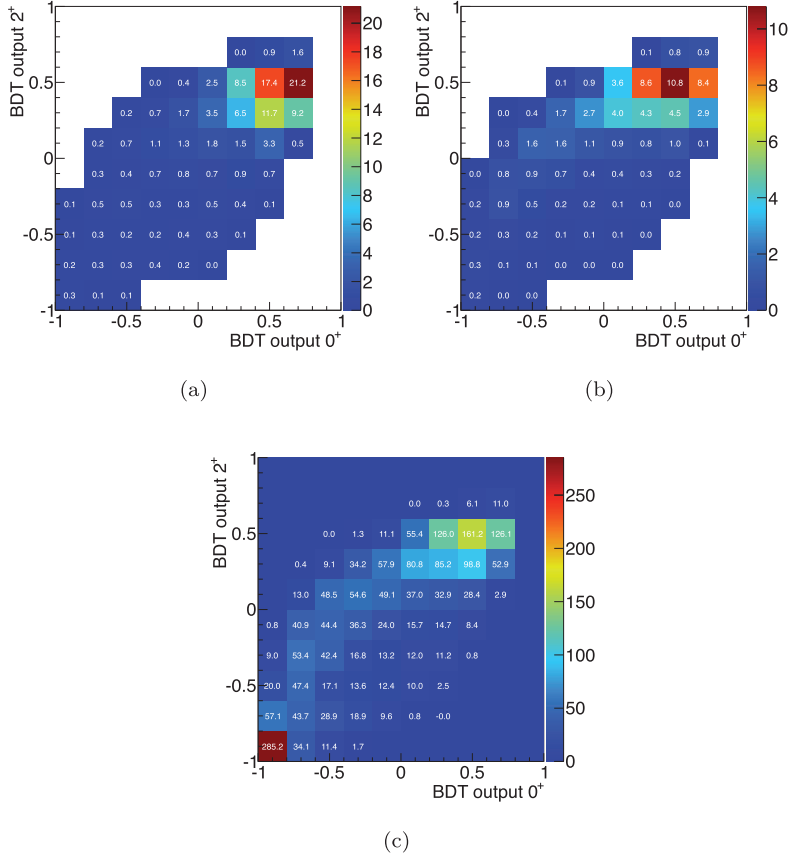


Figure 6.8: The two-dimensional distributions of the spin-0 signal (a), the spin-2 signal (b) and the background processes (c) in the two dimensional (BDT0, BDT2) space. The signal distributions are peaking towards the signal like region on both axes, while the background processes towards the background-like region close to -1 . In addition, the separating power between the signal hypotheses arises from the differences in the distributions of the respective peaks in the signal-like region of this space.

requirement on the invariant mass of the dilepton system is slightly loosened. This is motivated by the need to use the shape on the high-end of the distribution, since the region $m_{\ell\ell} > 80$ GeV is mainly background dominated and its information will add to the separation against the background processes. When the training is performed and the weights are collected, the method is then applied only in the region of $m_{\ell\ell} < 80$ GeV to reduce the background contamination of the region that enters into the fit.

Selection Before Training	Selection After Training	Z	W	Z_{exp}^0	Z_{exp}^2
$E_{T,rel}^{miss} > 20 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	yes	no	0.55	1.09
$E_{T,rel}^{miss} > 20 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.8$	yes	no	0.55	1.03
$E_{T,rel}^{miss} > 20 \text{ GeV}$	$E_{T,rel}^{miss} > 20 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8$	yes	no	0.64	1.19
$E_{T,rel}^{miss} > 20 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	yes	no	0.65	1.14
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$E_{T,rel}^{miss} > 20 \text{ GeV}$	no	no	0.92	1.89
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	no	no	1.11	2.01
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.8$	no	no	1.14	2.07
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.8, 60 < m_T < 150 \text{ GeV}$	$E_{T,rel}^{miss} > 20 \text{ GeV}$	no	no	1.04	1.99
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 2.8, 60 < m_T < 150 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	no	no	1.17	2.07
$E_{T,rel}^{miss} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}, ,$ $\Delta\phi_{\ell\ell} < 2.8, 60 < m_T < 150 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8$	no	no	1.24	2.12
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$E_{T,rel}^{miss} > 20 \text{ GeV}$	no	no	1.09	2.01
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	no	no	1.15	2.03
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8$	no	no	1.20	2.10
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	yes	yes	1.15	2.03
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8$	yes	yes	1.16	2.05
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8 \text{ GeV}$	$p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV}, \Delta\phi_{\ell\ell} < 2.8$	yes	yes	1.18	2.11
Chosen Configuration:					
$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 100 \text{ GeV},$ $\Delta\phi_{\ell\ell} < 2.8 \text{ GeV}$	$E_{T,rel}^{miss}, p_T^{\ell\ell} > 20 \text{ GeV}, m_{\ell\ell} < 80 \text{ GeV},$ $\Delta\phi_{\ell\ell} < 2.8 \text{ GeV}$	yes	yes	1.40	2.10

Table 6.2: List of analysis configuration in terms of selection requirements in the training (first column), signal region definition (second column), and if the $Z/\gamma^* + \text{jets}$ (third column) and the $W + \text{jets}$ (fourth column) had been included in the training phase as background processes. The results are given in terms of the expected sensitivity in Z values for the spin-0 (fifth column) and the spin-2 (sixth column) signal hypotheses.

6.2.3 BDT Settings Scan

Finally, an optimisation study is performed on the BDT settings in order to minimise any possible effect it may have on the training phase. The configuration as far as the settings is based on the one used for the observation study in Ref. [149]. However, these settings may not be optimal for the spin studies. A scan was performed on the maximum number of levels the method can proceed (referred to as *MaxDepth*) and the minimum number of events each terminal node should have. The quantitative result is given in probability of the Kolmogorov-Smirnoff (KS) test between the training and testing BDT discriminants of the signal and background events.

Table 6.3 shows the comparison of the KS test in the signal and background

discriminants of each training when varying the MaxDepth of the method. The initial value was set at 3. The scan proves that the best-performing choice, balanced over both the trainings, is the MaxDepth= 5 option.

Training	MaxDepth=3 KS Value S (B)	MaxDepth=4 KS Value S (B)	MaxDepth=5 KS Value S (B)
Spin-0	0.948 (0.876)	0.334 (0.711)	0.824 (0.839)
Spin-2	0.130 (0.0786)	0.0768 (0.125)	0.158 (0.131)

Table 6.3: Kolmogorov-Smirnoff test probabilities for the shapes of BDT discriminant in Signal (Background) as a function of MaxDepth when scanning the MaxDepth values for the two trainings (spin-0 and spin-2). The most balanced option is the case with MaxDepth=5.

Finally, in a similar regime, choosing the best performing value for MaxDepth to be 5, a similar scan on the minimum events in the terminal nodes is performed. Table 6.4 summarises the result for both trainings. The minimum value of 2000 events was chosen for both trainings.

Training	1000 events KS Value S (B)	2000 events KS Value S (B)	4000 events KS Value S (B)
Spin-0	0.583 (0.103)	0.824 (0.893)	0.80 (0.98)
Spin-2	0.0534 (0.160)	0.158 (0.131)	0.103 (0.713)

Table 6.4: Kolmogorov-Smirnoff test probabilities for the shapes of BDT discriminant in Signal (Background) as a function of nEventsMin when scanning the parameter values for the two trainings (spin-0 and spin-2). The most balanced option is the case with nEventsMin to be 2000 events.

The final overall configuration of the parameters settings as suggested from these studies is modified and is shown in Table 6.5. In addition, Figure 6.9 shows the overtraining checks performed on the BDT response, comparing the one of the training and the one of the testing sample for the signal and the background processes. Figure 6.9a corresponds to the BDT0 training, while Figure 6.9 to the BDT2 training.

BDT parameter	Value
BoostType	Gradient
MaxDepth	5
NTrees	400
nEventsMin	2% of signal events (about 2000 events)
UseBaggedGrad	true
GradBaggingFraction	0.5
Shrinkage	0.1

Table 6.5: BDT parameters used in the analysis.

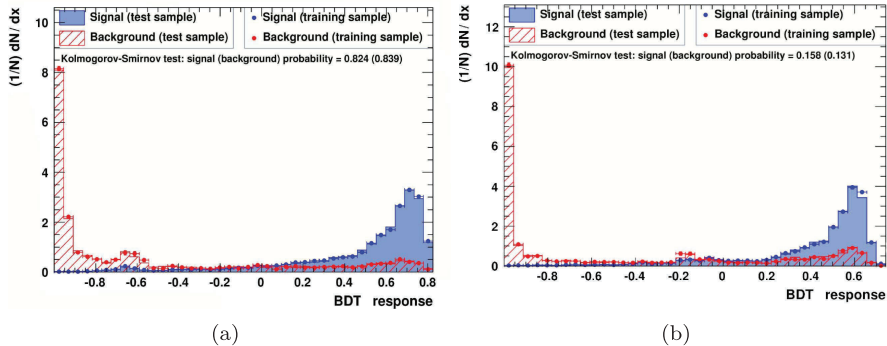


Figure 6.9: BDT response distribution for the signal and the background processes, comparing the Kolmogorov-Smirnoff test probabilities between the training and the testing sample. (a) is for the BDT0 training, while (b) is for the BDT2 training. The BDT settings used are $MaxDepth = 5$ and $nMinEvents = 2000$ events.

6.2.4 Optimization on Production Mechanism for Spin-2

Since the production mechanism for a spin-2 resonance is unknown, it is parametrised in terms of the $f_{q\bar{q}}$ fraction. However, the different production $f_{q\bar{q}}$ fraction implies a different kinematic behaviour in the final state for the signal events. Figure 6.10 shows the shapes of input variable distributions and the BDT output discriminants as a function of the $f_{q\bar{q}}$ fraction. The variations on the shapes are not negligible, therefore different production mechanisms would have different response of the decision tree. To maximise the separation power for the different production mechanisms, the method is trained five times, one per each $f_{q\bar{q}}$ value. Each of the training weights corresponding to different production mechanisms is applied on the testing sample. Thus, the results for the spin-2 studies are presented as a function of the $f_{q\bar{q}}$ fraction, corresponding to a $f_{q\bar{q}}$ dependent training for spin-2.

6.3 Analysis for Spin-1

Although the analysis strategy developed is optimised to be able to separate the spin-0 SM hypothesis from the spin-2, the analysis is powerful enough to also separate the SM signal from spin-1 $^\pm$ hypotheses. For these two studies, the same analysis strategy is employed, the only change being that the second BDT is now trained to separate the spin-1 $^+$ (spin-1 $^-$) against the SM background processes, when the study refers to separating the SM spin hypothesis from the alternative spin-1 $^+$ (spin-1 $^-$). The ranking of the input variables is similar to the spin-2 analysis with the importance of $p_T^{\ell\ell}$ and $m_{\ell\ell}$ variables switched.

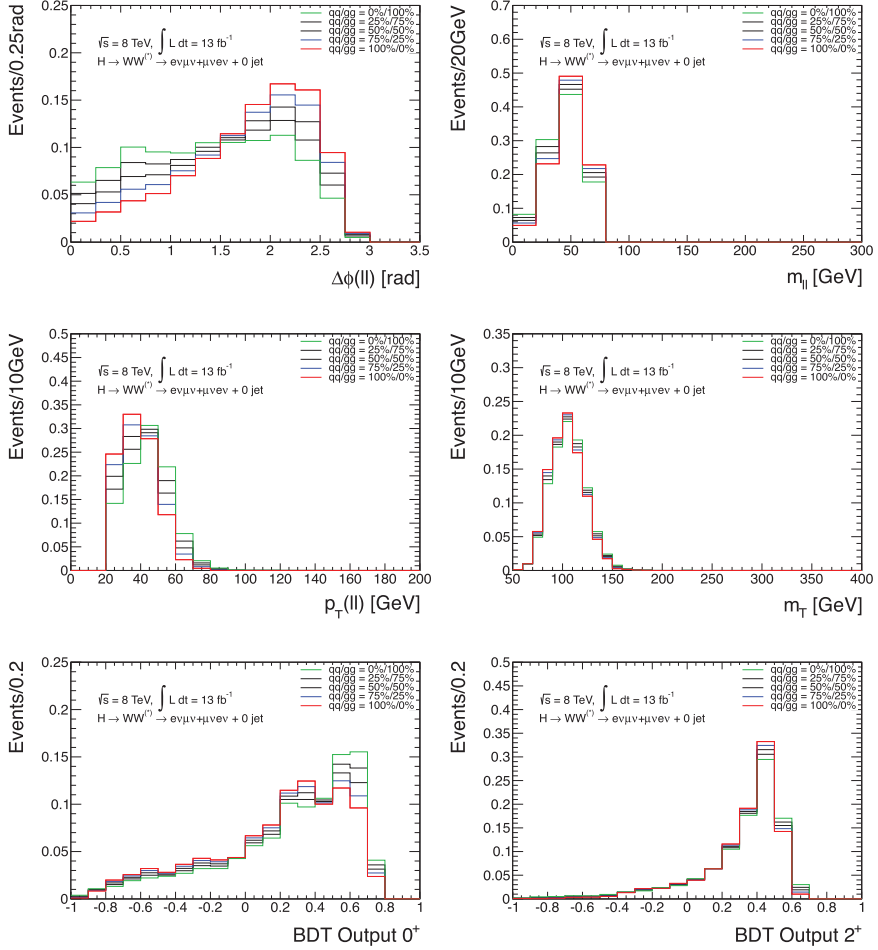


Figure 6.10: Shapes of the input variables distributions and the BDT output discriminant of the two trainings. The shapes are drawn after the $p_T^{\ell\ell}$ selection requirement. The plots show the shape variations in the spin-2 signal for different production mechanisms, as parametrised by the $f_{q\bar{q}}$ fraction. The non-negligible shape variations lead to the need of re-training the method.

hypotheses are concerned.

Figure 6.13 shows the shapes of the BDT output discriminant for the two BDTs trained in the spin-1⁺ and spin-1⁻ studies respectively. The Monte Carlo is unblinded in these plots, since no data-points are shown.

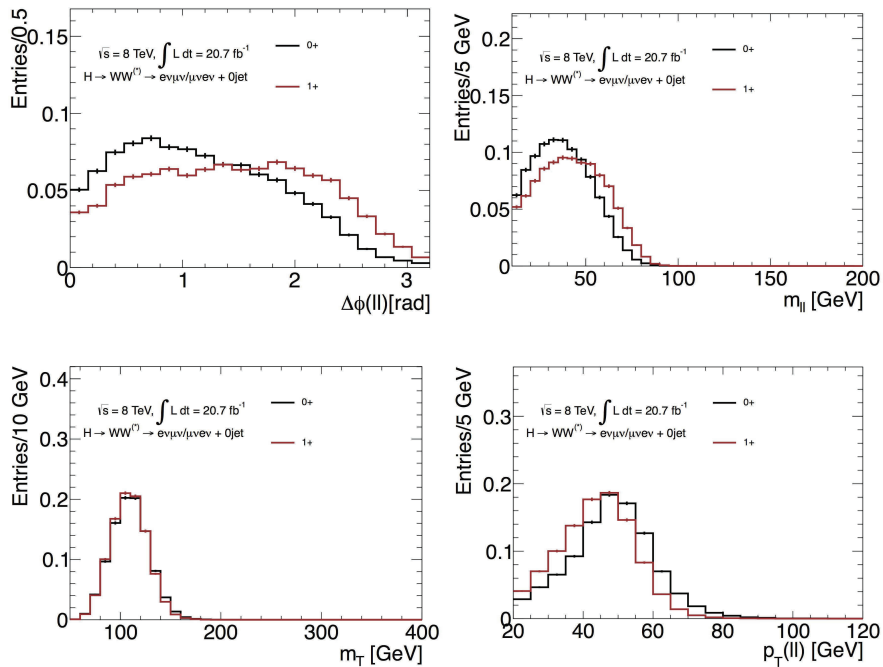


Figure 6.11: Shapes of the input variables distributions comparing the shapes of the spin-0 SM signal hypothesis and the spin-1⁺ one. The distributions are drawn after the $E_{T,rel}^{miss}$ and $p_T^{\ell\ell}$ preselection requirements.

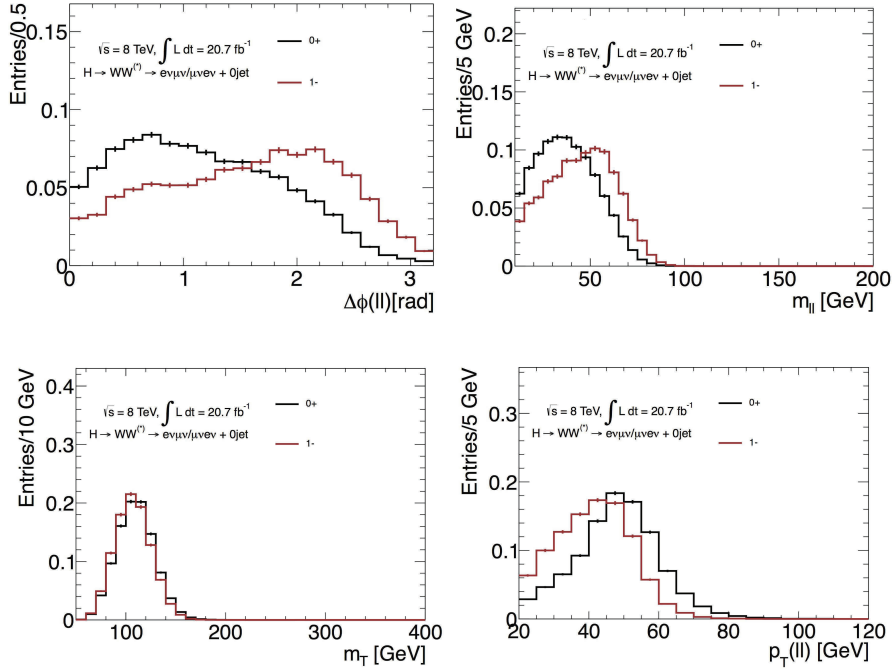


Figure 6.12: Shapes of the input variables distributions comparing the shapes of the spin-0 SM signal hypothesis and the spin-1⁻ one. The distributions are drawn after the $E_{T,\text{rel}}^{\text{miss}}$ and $p_T^{\ell\ell}$ preselection requirements.

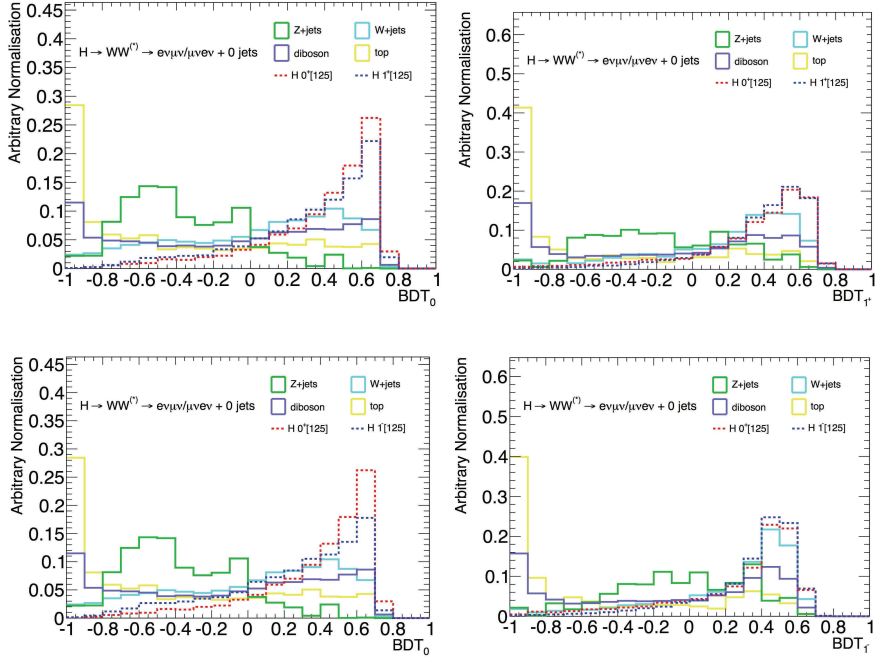


Figure 6.13: Shape distributions of the BDT output discriminant in the signal region, for each of the two trainings (left and right) for the spin- 1^+ (top) and the spin- 1^- study.

6.4 Background Validation

As the analysis relies on the correct estimate of the shape of the background it is important to validate the modelling of the background by the Monte Carlo simulation. In addition the BDT makes use of the correlations between the input variables, therefore also those must be modelled correctly. In the following subsections the modelling of the background is investigated.

6.4.1 Modelling of the Input Variables

To verify that the Monte Carlo models correctly the input variables as observed in the data, is crucial for the analysis, since these are the variables that the BDT is trained on, and therefore are used to make decisions on separating the signal from background. The test of the modelling of the input variables is done in the control regions. Thus, the input variables are plotted in the WW and in the $Z/\gamma^* + \text{jets}$ control regions and the agreement between the Monte Carlo and the data is tested.

Figures 6.14 and 6.15 show the input variables in the WW and $Z/\gamma^* + \text{jets}$ control regions. The ratio in the bottom of each plot tests the agreement between the data and the background expectation. No mis-modelling is observed for the 2013 simulated samples, as far as the input variables are concerned, since the agreement is well within the statistical and systematic uncertainties.

6.4.2 Correlations between the input variables

In addition, to verify that the correlations between the input variables of the BDT are modelled correctly by the Monte Carlo, the correlation factor $C(i)$ is calculated per event i in the control region of the irreducible WW SM background process as

$$C(i) = \frac{(x(i) - \bar{x}) \cdot (y(i) - \bar{y})}{\sigma_x \cdot \sigma_y}, \quad (6.1)$$

where $x(i)$ and $y(i)$ are the values of the variables x and y , respectively and $\bar{x}$, $\bar{y}$ are the mean values of the corresponding distributions over all events i , while σ_x and σ_y are the standard deviations. The results are summarised in Table 6.6 and are all in very good agreement between the data and the Monte Carlo simulated backgrounds.

	$\Delta\phi_{\ell\ell} \ m_{\ell\ell}$	$\Delta\phi_{\ell\ell} \ m_T$	$\Delta\phi_{\ell\ell} \ p_T^{\ell\ell}$	$m_{\ell\ell} \ m_T$	$m_{\ell\ell} \ p_T^{\ell\ell}$	$m_T p_T^{\ell\ell}$
data	0.35 ± 0.02	0.07 ± 0.02	-0.38 ± 0.02	0.95 ± 0.02	0.11 ± 0.02	0.48 ± 0.02
background	0.38 ± 0.01	0.13 ± 0.01	-0.34 ± 0.01	0.99 ± 0.01	0.12 ± 0.01	0.45 ± 0.01

Table 6.6: Table of the mean of the correlation distributions between the input variables in the WW control region.

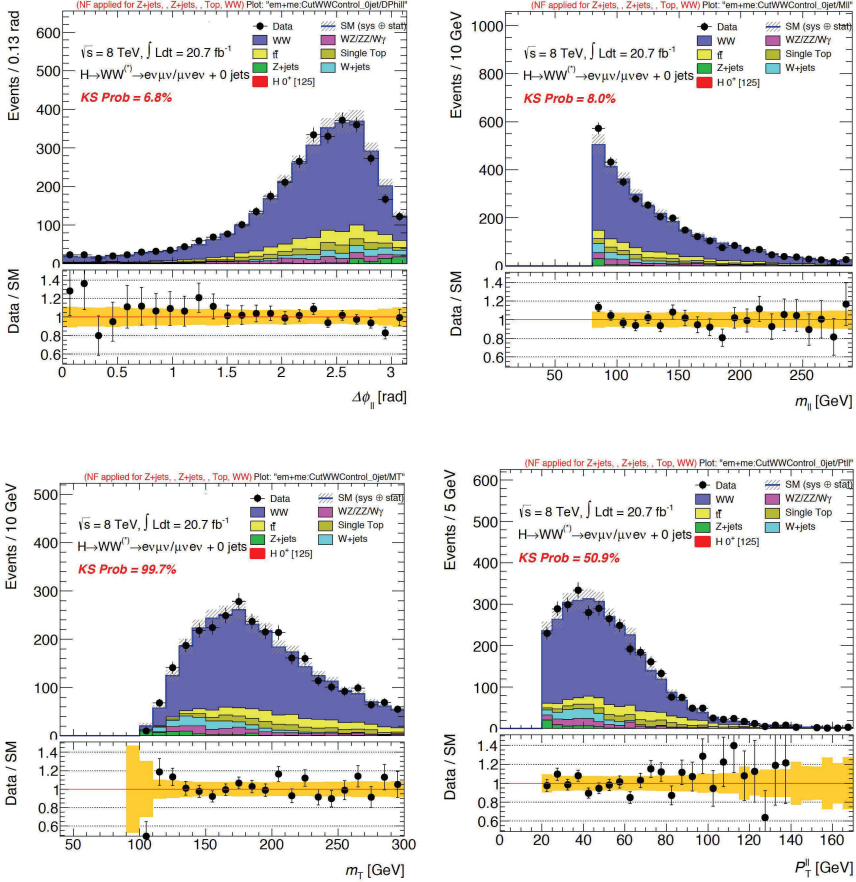


Figure 6.14: Input variables of the BDT plotted in the WW control region. The lower part of each plot shows the ratio between the data and the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.

6.4.3 Modelling of the BDT Discriminant

As for the input variables, the output BDT discriminant should be well modelled. This is also tested in the control regions. Figure 6.16 shows the BDT output discriminants for the spin-0 and the spin-2 BDTs. The plots are shown in the control regions. As expected, since the BDT is trained to separate signal from background, most events are accumulated close to the -1 background-like bin of the BDT in the background enriched area.

Similarly, Figure 6.17 shows the BDT output distributions in the two con-

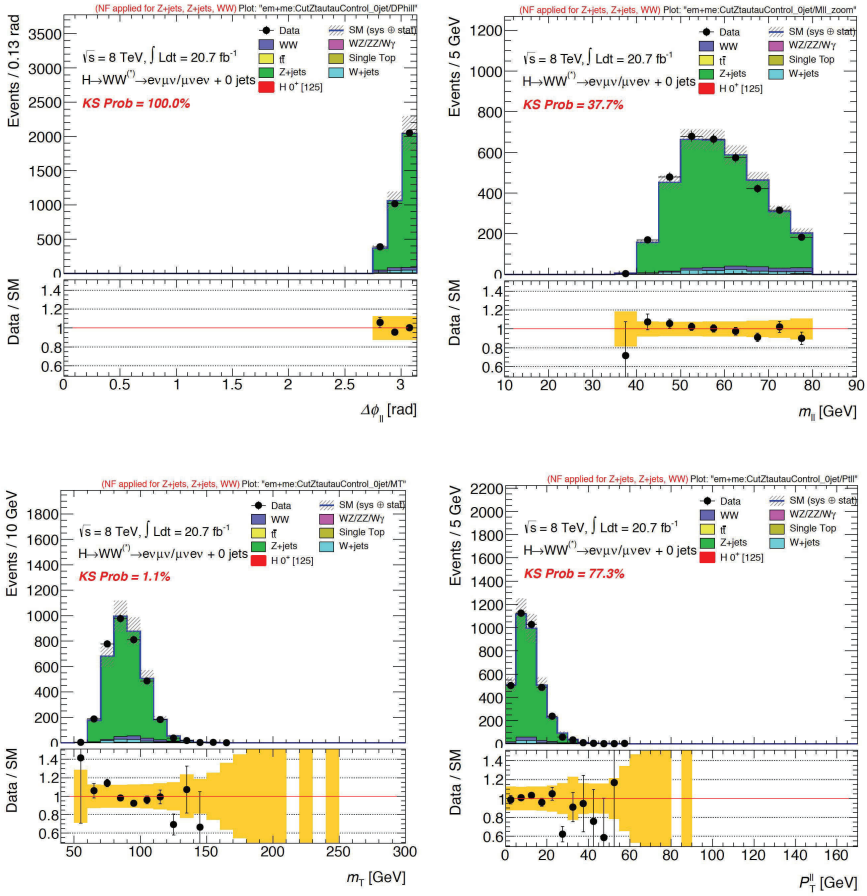


Figure 6.15: Input variables of the BDT plotted in the $Z/\gamma^* + \text{jets}$ control region. The lower part of each plot shows the ratio between the data and the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.

control regions for the spin- $1^\pm$ BDTs. In this figure, the BDT output for the spin-0 case is omitted as it is the same as in Figure 6.16. Below each plot, the ratio compares the agreement of the data with the Monte Carlo expectation. The orange band represents the statistical plus systematic uncertainty band. No mis-modelling is observed, since small variations are well within the uncertainties.

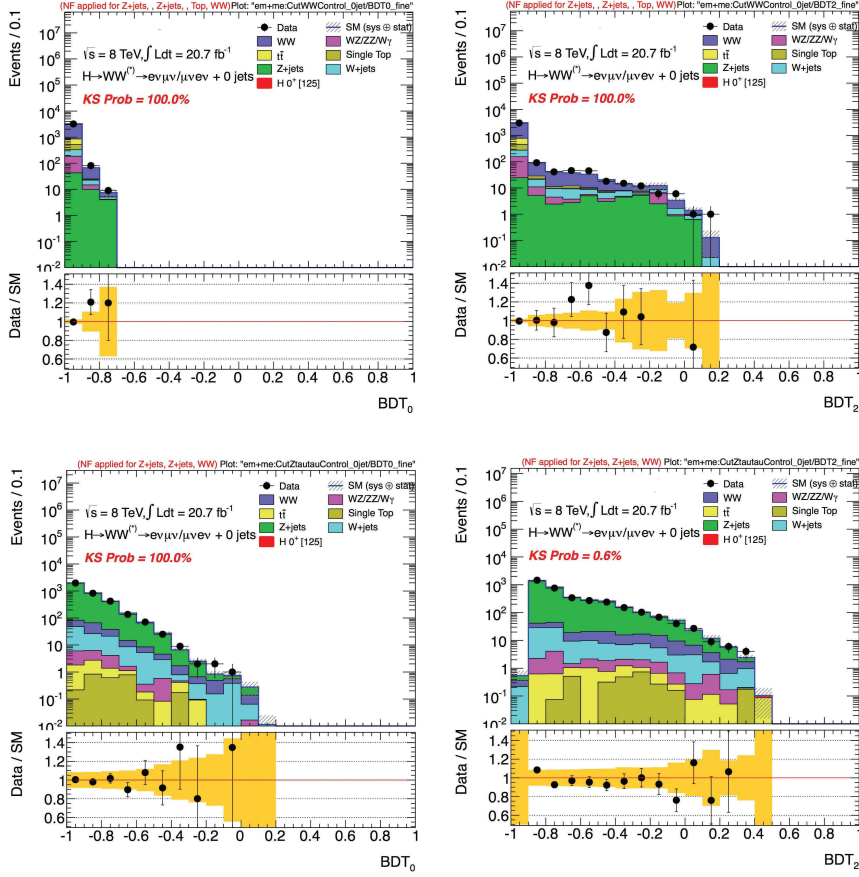


Figure 6.16: The distribution of the BDT output discriminants for the spin-0 and spin-2 decision trees. The distributions are plotted in the WW control region (top) and in the $Z/\gamma^* + \text{jets}$ control region (bottom). The lower part of each plot shows the ratio between the data and the background expectation. The orange band in the bottom ratio plot represents the statistical plus systematic uncertainty band.

6.4.4 Training of one of the SM backgrounds against other SM backgrounds

As mentioned, when the BDT output distributions are plotted in the control regions, by construction, most of the events are accumulated close to the background-like bin at -1 . This makes hard the process of validating that the BDT output is well modelled in the background enriched regions. To alleviate this issue, a BDT is trained using one of the major backgrounds as signal,

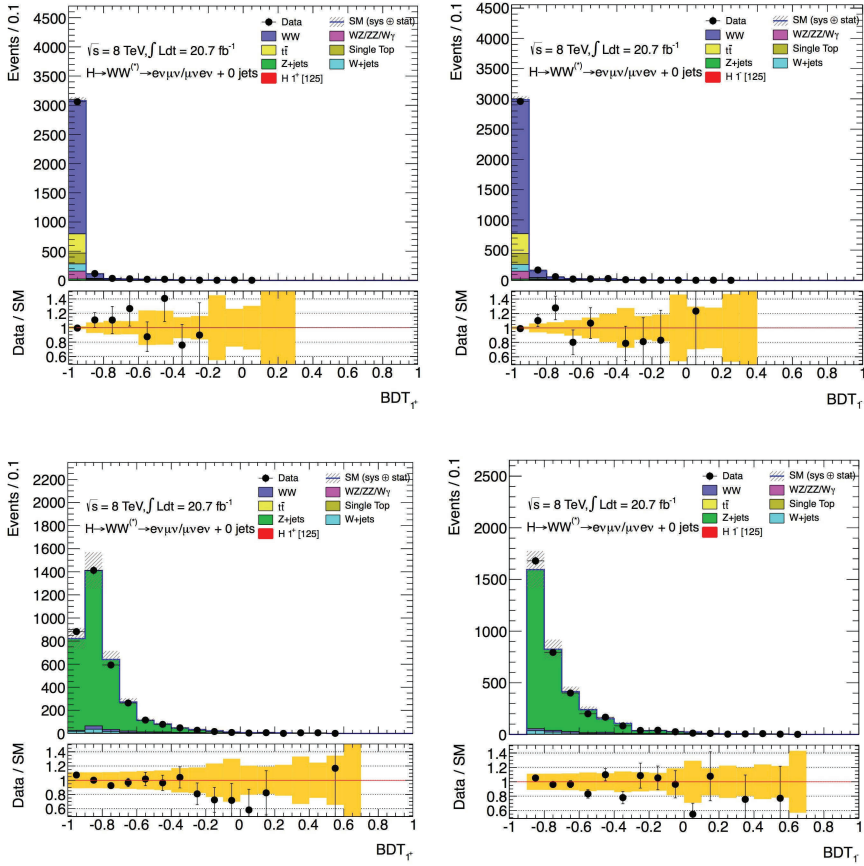


Figure 6.17: The distribution of the BDT output discriminants for the spin-1⁺ (left) and spin-1⁻ (right) decision trees. The distributions are plotted in the WW (top row) and $Z/\gamma^* \rightarrow \tau\tau$ (bottom row) control regions. The lower part of each plot shows the ratio between the data and the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band. Only the decision trees trained with the spin-1 samples are shown, since the ones with the spin-0 samples are identical as in Figure 6.16.

and tests this against all the remaining background processes. Therefore, one BDT is trained with the WW against all the remaining background processes, to check the modelling of the BDT for the WW background. Similarly, the top-quark background is trained against the remaining background processes. The Higgs signal process is not used for these trainings. In addition, the BDT input variables and parameter settings remain exactly the same as for the nominal, signal versus background training. The only exception to this is the

$m_{\ell\ell} < 100$ GeV requirement in the training. This has to be dropped, since it removes most of the WW (top-quark) background events, which are now "signal" in this special training.

The BDT output distributions of these trainings are shown in Figure 6.18 in the WW control region. No mis-modelling of the BDT distribution is observed in the control region, since the variations are within the statistical and systematic uncertainty.

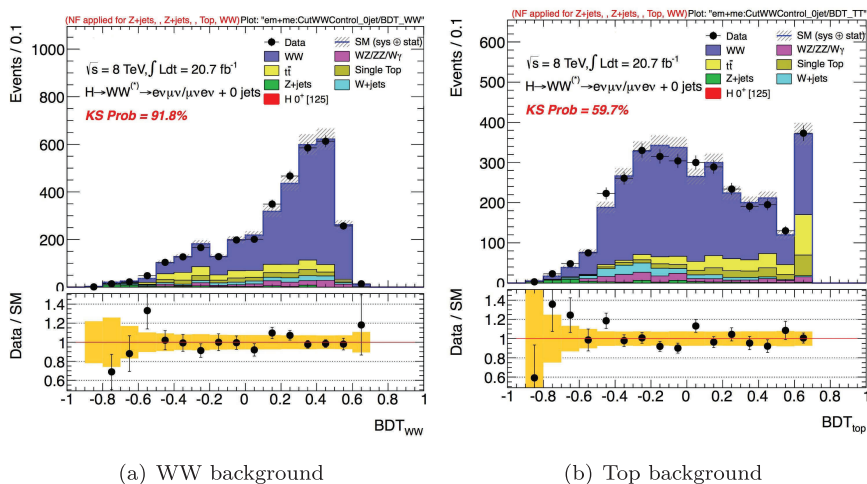


Figure 6.18: (a) BDT distribution for the training of the WW background against the remaining background processes, in the WW control region. (b) Similarly, training of the top-quark background against the remaining background processes, in the control region. The lower part of each plot shows the ratio between the data and the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.

6.5 Impact of Systematic Uncertainties

A careful treatment of the systematic uncertainties is crucial for the properties measurement in $H \rightarrow WW^*$. In this section, the uncertainties are discussed in two broad categories: experimental or detector sources, such as Jet Energy Scale (JES), and theoretical sources such as the uncertainty on the p_T spectrum of the Higgs boson.

6.5.1 Detector Systematic Uncertainties

Systematic uncertainties arise from potential mis-modelling of the jet and lepton energy scales and resolutions, the lepton identification efficiency, as well as the resolution on the measurement of E_T^{miss} . The main sources of systematic uncertainty considered in this analysis are summarised in Table 6.7. A short description is also included in the table, summarising the discussion presented in Chapter 3. To ascertain their impact on the analysis, Monte Carlo samples with systematically varied parameters were studied, and the uncertainties were used as nuisance parameters in the fit (see Section 6.6). While, many of the systematic uncertainties are negligible, the dominant sources of uncertainty are listed in Table 6.8 along with the effect they have on the background and signal yields in the signal region after the $\Delta\phi_{\ell\ell}$ selection.

Source of Uncertainty	Treatment in the analysis
Jet Energy Resolution (JER)	MC jet resolution smeared using jet p_T , η -dependent parametrization
Jet Energy Scale (JES)	Global JES: 2-9% depending on jet p_T , η and sample composition for jets with $p_T > 25$ GeV and $ \eta < 4.5$ Pileup: 0.5-10% depending on jet p_T , η and sample composition Gluon fraction uncertainty and uncertainty from close-by jets included
Electron Selection Efficiency	Separate systematics for electron identification, reconstruction and isolation, added in quadrature Identification: 3% for $p_T \sim 15$ GeV, decreasing to 1% for $p_T > 30$ GeV in the central region Reconstruction: 0.6 - 1.1% for $p_T > 15$ GeV trigger: 1-2% uncertainty Total uncertainty of 2-5% depending on η and E_T
Electron Energy Scale	Uncertainty smaller than 1%, depending on η and E_T
Electron Energy Resolution	Energy varied within its uncertainty, 0.6% of the energy at most
Muon Selection Efficiency	0.3-1% as a function of η and p_T
Muon Momentum Scale and Resolution	Uncertainty smaller than 1%
Missing Transverse Energy	Lepton and hard jet energy uncertainties propagated to E_T^{miss} using METUtility package Soft terms: ± 1 GeV uncertainty on energy scale; energy resolution uncertainty as a function of total p_T of hard objects and primary vertex multiplicity
Luminosity	3.6% [150]

Table 6.7: Experimental sources of systematic uncertainty per object or event.

Since this analysis depends on the shapes of kinematic distributions for a spin-0 or spin-2 Higgs hypothesis (and thus implicitly on the background shapes), it is imperative to ascertain whether these sources affect only the overall normalization of the backgrounds and expected signal yields, or whether the kinematic distributions are distorted by, for example, a modified JES. In order to determine this, Monte Carlo samples with systematically varied parameters were analysed.

The final distribution that is used as a properties discriminator is compared for the nominal and systematically varied samples. Whether the variation in-

Source of Uncertainty	Spin 0	Spin 2	Spin 1 ⁺	Spin 1 ⁻	WW	W+j	Z/ γ^* +j	Top	Tot. Backgr.
Jet Energy Scale	4.7%	4.2%	2.8%	2.9%	0.8%	—	9.6%	2.9%	1.0%
W+jet(s) Fake Factor	—	—	—	—	2.9%	50%	—	—	3.4%
Lepton ID Efficiency	3.2%	3.1%	3.2%	3.3%	1.0%	—	3.7%	1.0%	1.1%
E_T^{miss}	0.3%	0.3%	0.3%	0.3%	0.1%	—	6.3%	1.4%	0.5%
MC Statistics	0.9%	0.8%	0.6%	0.7%	0.6%	—	5.2%	2.3%	0.7%

Table 6.8: Largest systematic uncertainties on signal (spin-0, spin-1[±], and spin-2), on dominant background processes, as well as and on the total background yields in the signal region.

duces a shape distortion is defined by a Kolmogorov-Smirnov test, in which the probability that the varied and nominal shapes arise from the same underlying distribution, KS must be smaller than 20%.

Figures 6.19, 6.20 show some of these tests for the electron, muon and soft term scale and resolution systematics for the one dimensional BDT0 and BDT2 distributions, respectively, for the Higgs signal. Similarly, Figures 6.21 and 6.22 show the same distributions for the background samples. Only few plots selected plots are shown for illustration purposes. Figure 6.23 shows the summarised KS test probabilities for all the detector systematics for each systematically varied MC sample. The labels on the horizontal axis represent a systematic uncertainty. The systematics that include the string "JES" in their name, correspond to uncertainties related to the Jet Energy Scale, while "JER" corresponds to the Jet Energy Resolution. In the same way, labelled by "MET" are the Missing Transverse Energy related systematics, the "tag" string corresponds to flavour-tagging related uncertainties, and "Trigger" and "Iso" correspond to the total uncertainty related to the trigger and isolation efficiencies, respectively. Finally, labels including "Elec" and "Mu" correspond to systematics related to the scale and resolution of electrons and muons respectively. As can be seen, the shapes of the varied MC samples are in complete agreement with the nominal Monte Carlo predictions. Therefore, only overall normalisation uncertainties are profiled in the fit procedure for the sources listed in Table 6.7.

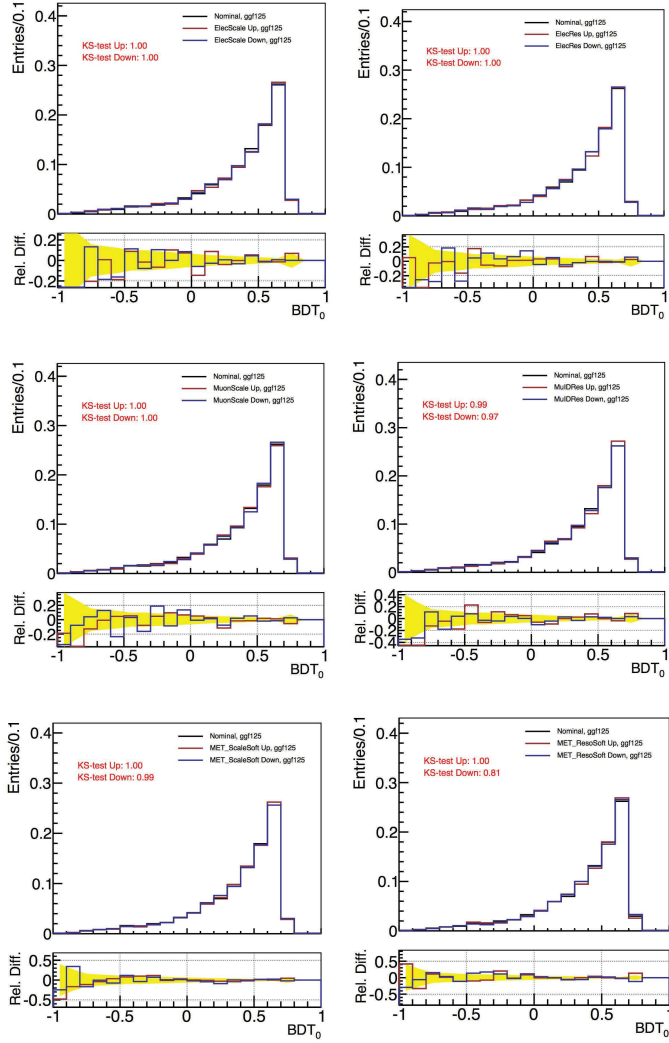


Figure 6.19: Comparison of shapes between the nominal and the up and down systematic variations on the BDT₀ distribution for the signal sample. The electron (top row), muon (middle row) and the soft-terms of the E_T^{miss} calculation objects are shown for the scale (left) and resolution (right) systematics. The lower part of each plot shows the ratio between the nominal and the up and down systematic variations.

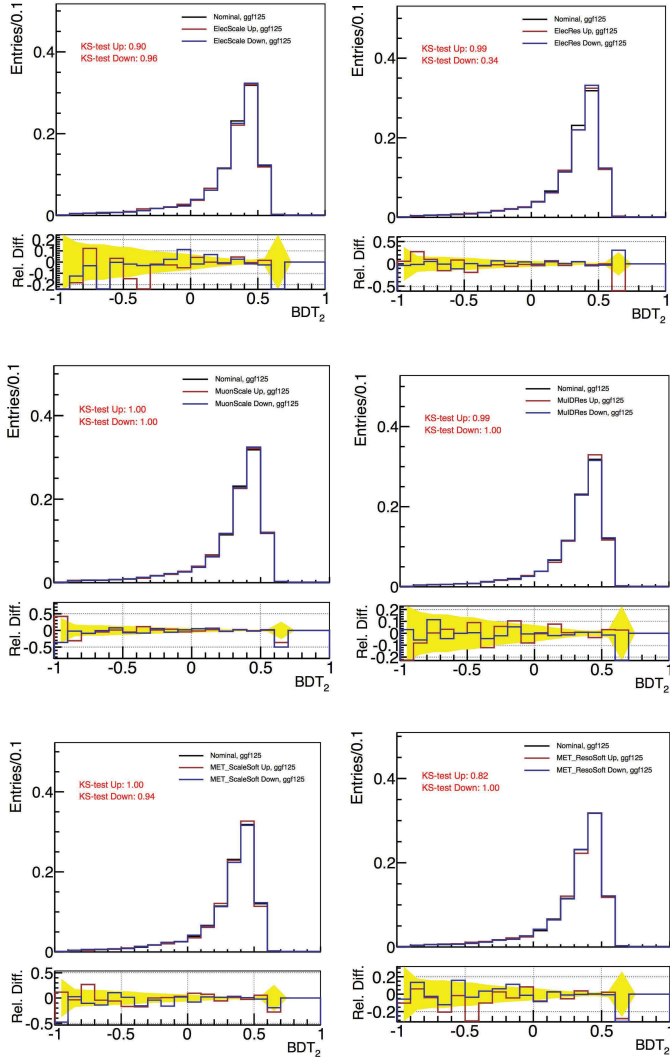


Figure 6.20: Comparison of shapes between the nominal and the up and down systematic variations on the BDT2 distribution for the signal sample. The electron (top row), muon (middle row) and the soft-terms of the E_T^{miss} calculation objects are shown for the scale (left) and resolution (right) systematics. The lower part of each plot shows the ratio between the nominal and the up and down systematic variations.

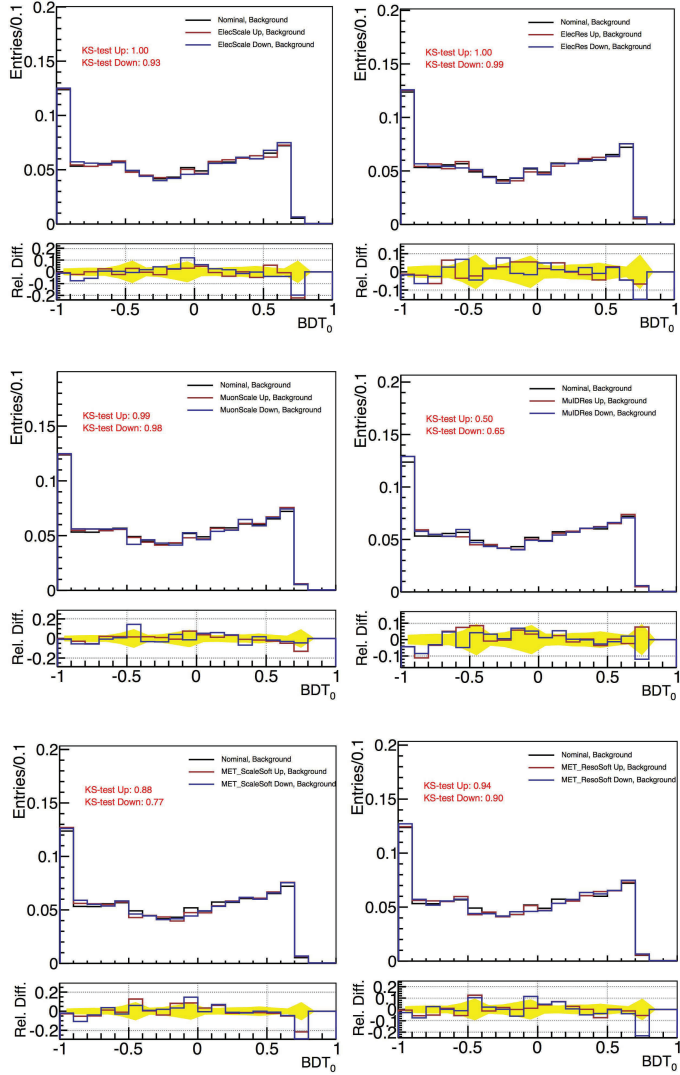


Figure 6.21: Comparison of shapes between the nominal and the up and down systematic variations on the BDT0 distribution for the background samples. The electron (top row), muon (middle row) and the soft-terms of the E_T^{miss} calculation objects are shown for the scale (left) and resolution (right) systematics. The lower part of each plot shows the ratio between the nominal and the up and down systematic variations.

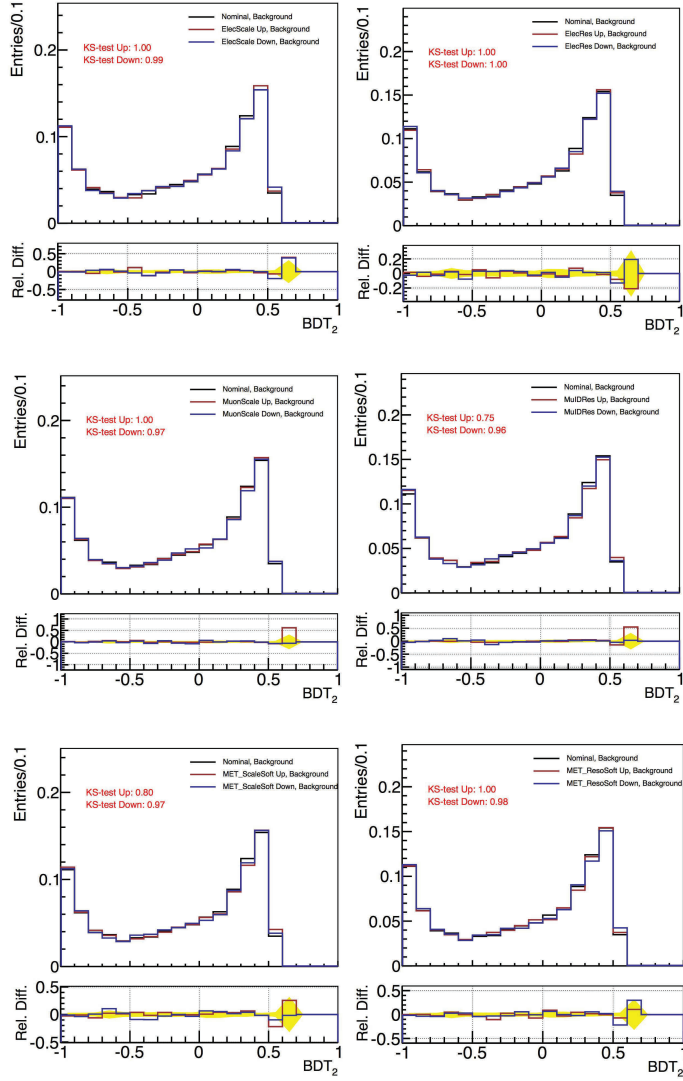


Figure 6.22: Comparison of shapes between the nominal and the up and down systematic variations on the BDT_2 distribution for the background samples. The electron (top row), muon (middle row) and the soft-terms of the E_T^{miss} calculation objects are shown for the scale (left) and resolution (right) systematics. The lower part of each plot shows the ratio between the nominal and the up and down systematic variations.

- *uncertainty on QCD scale choice*: the MCFM [141] generator is used and the renormalisation and factorisation scales are varied by a factor of 2 while keeping the relative ratio between 0.5 and 2.0 ;
- *uncertainty on the PDF set choice*: calculated using the error sets provided by CTEQ and comparing the predictions from CTEQ [136] and MRST [137];
- *uncertainty on the generator modelling*: comparing the predictions of POWHEG and MCFM;
- *uncertainty on the choice of modelling the underlying event and the parton shower*: computed by comparing the POWHEG+ PYTHIA8 to POWHEG+ HERWIG.

The evaluated uncertainties are summarised in Table 6.9. The sources of systematic uncertainties on the normalisation of the WW background are treated independently in the final fit and are considered uncorrelated.

α	Scale	Modelling	PDF's (eigenvectors)	PDF's (parametrisation)	total
SR/CR	1.1%	4.0%	2.3%	0.7%	4.8%

Table 6.9: Theoretical uncertainties on the extrapolation factor α for the WW background process. A total uncertainty of 4.8% is estimated. The sources of the uncertainty are treated independently in the fit and are considered uncorrelated.

Another important uncertainty is the modelling of the shape of the WW background. This shape is evaluated in the two BDT discriminants that enter the final fit. The scale uncertainty on the MC prediction is studied by varying, the factorisation and renormalisation scales similar to what have been done for the normalisation uncertainty. The parton shower modelling uncertainty is evaluated by comparing HERWIG and PYTHIA6 parton showering programs. Finally, the PDF uncertainty is estimated by combining the CT10 [135] PDF error set with the difference in central values of NNPDF [144] and MSTW [143] compared to CT10 central value. The largest variation for each uncertainty in a specific bin of a BDT discriminant is taken as a two-sided systematic uncertainty, resulting in an envelope around the nominal value. The uncertainty on the BDT shape is within $\pm 1\%$ of the nominal.

The scale, parton shower and PDF uncertainties are all treated independently in the final fit of the 2D space made from the BDT discriminants. For each uncertainty a two-sided envelope is derived.

6.5.2.2 Higgs Modelling

A significant uncertainty arises from the lack of knowledge in the production mechanism for a 2^+ Higgs boson. While for the SM hypothesis, the Yukawa and gauge coupling are requisite predictions, for a 2^+ resonance the relative coupling strengths are unclear a priori. For example a 2^+ 'Higgs' may couple directly to massless particles.

This uncertainty can be split into two different ones. One is that the helicity combinations for $q\bar{q}$ and gg production are different and therefore the angular distributions in the final state vary significantly. The second one is that the production mode, in principle, has a non-negligible impact on the underlying p_T spectrum of the Higgs boson. This is due to the fact that the radiative effects are enhanced in gluon initial states with respect to quark ones.

Furthermore, the underlying transverse momentum of the Higgs boson has an impact on the final-state observables. This is shown in Figure 6.24, where the input variables of the BDT are shown after re-weighting the $q\bar{q}$ events in the sample by $f(p_T)$, where

$$f(p_T) = \frac{N^{NLO}(p_T)}{N^{LO}(p_T)}. \quad (6.2)$$

Thus, the events are re-weighted by the ratio of the full NLO p_T spectrum to the LO one. The distributions are shown after the $E_{T,rel}^{miss}$ preselection requirement. However, the shown differences become negligible when the selection criteria are applied. This is shown in Figure 6.25. Thus, this source of systematic uncertainty is neglected in the final fit.

Finally, no additional systematic uncertainty associated to the Higgs p_T for the SM Higgs is considered. This is due to the fact that POWHEG was re-weighted to HqT 2.0 [151]. Thus the calculation is derived at NNLL+NLO. Thus a systematic uncertainty on the calculation has negligible impact with respect to the ones already mentioned.

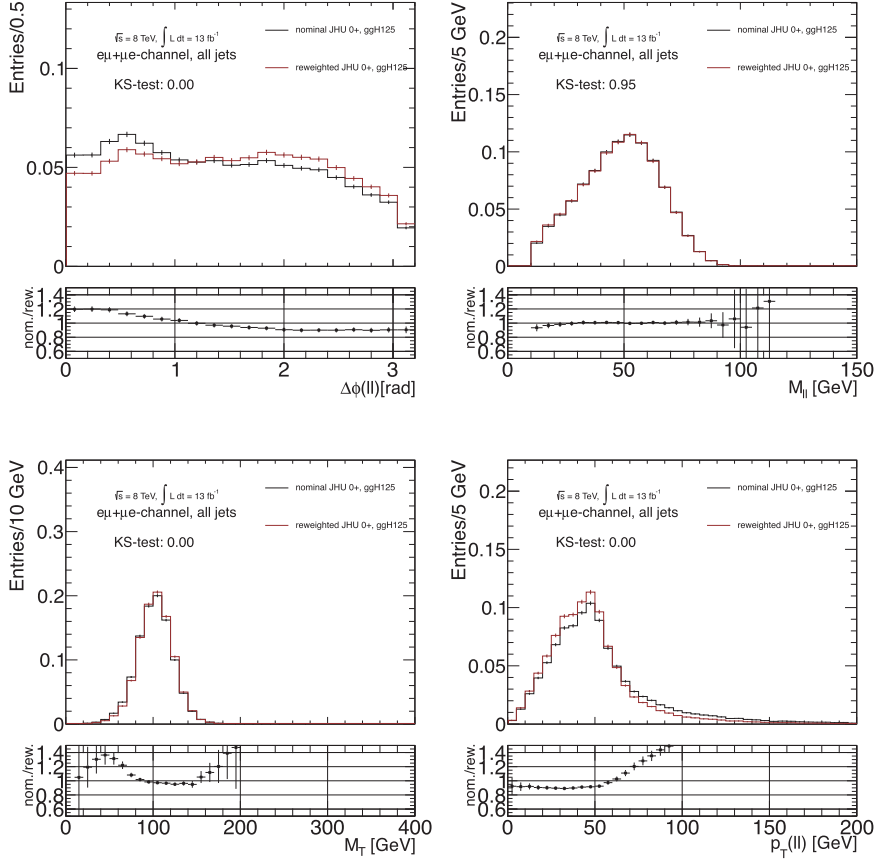


Figure 6.24: Effect of the Higgs p_T distribution in spin-0 events on input variables for the BDT analysis after the $E_{T,\text{rel}}^{\text{miss}}$ pre-selection requirement. Below each plot, the ratio of the two distributions is shown. The error bars include only statistical uncertainties.

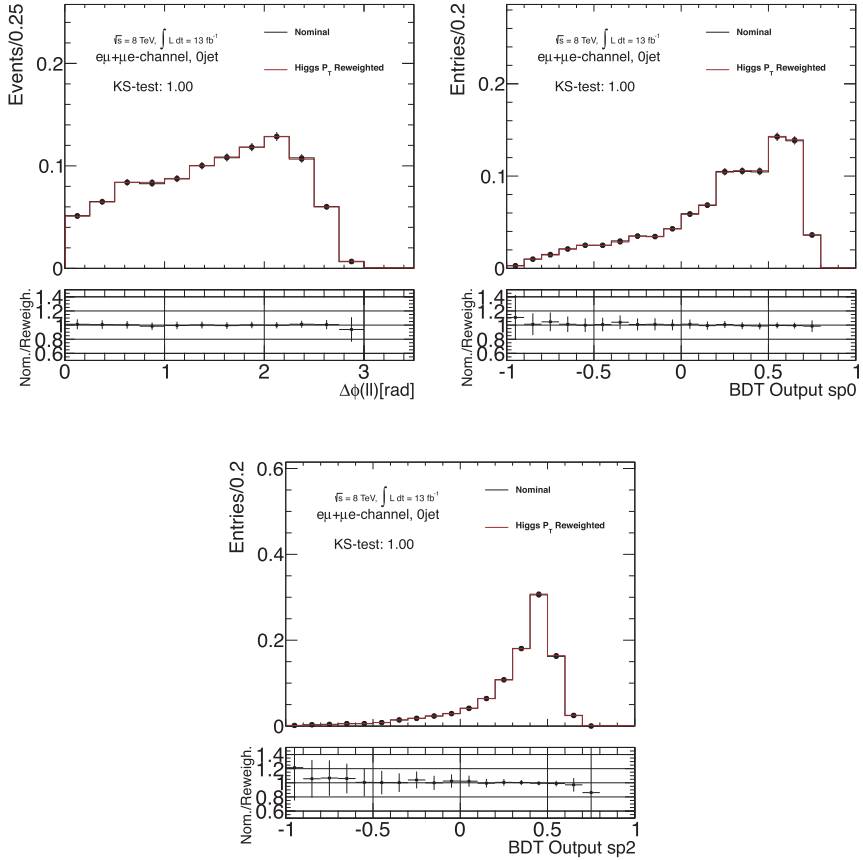


Figure 6.25: Effect of the Higgs p_T distribution in 0^+ events on the $\Delta\phi_{\ell\ell}$ and on the BDT discriminants. The plots are after applying the full selection requirement. Below each plot, the ratio of the two distributions is shown. The error bars include only statistical uncertainties.

6.6 Statistical Treatment

For the statistical treatment of the analysis, a binned likelihood is constructed with one parameter of interest. The parameter of interest $\varepsilon \in (0, 1)$ represents the fraction of spin-0 signal events in the total signal expectation with respect to the spin-0 ones. Therefore, $\varepsilon = 0$ represents the spin-2 hypothesis, while $\varepsilon = 1$ represents the spin-0. The overall signal normalisation (signal strength) $\mu > 0$ is included as a nuisance parameter. Nuisance parameters in a likelihood definition are parameters which must be accounted for, but are not of immediate interest. To construct the binned likelihood, template histograms are created to represent the nominal signal and background rates. The histogram represents the one dimensional unrolled BDT0×BDT2 distribution. The systematic uncertainties are represented via nuisance parameters, θ , with each one having auxiliary constraints $\mathcal{A}(\tilde{\theta}|\theta)$. The likelihood is written as

$$\mathcal{L}(\varepsilon, \mu, \vec{\theta}) = \prod_i^{N_{\text{bins}}} P(N_i | \mu(\varepsilon S_{0+,i}(\vec{\theta}) + (1 - \varepsilon) S_{2+,i}(\vec{\theta}) + b_i(\vec{\theta})) \times \prod_i^{N_{\text{sys}}} \mathcal{A}(\tilde{\theta}_i | \theta_i). \quad (6.3)$$

The statistical test employed for the final result is based on the likelihood ratio between the two hypotheses, expressed as

$$q = -2 \ln \frac{\mathcal{L}(\varepsilon = 1, \hat{\mu}_{\varepsilon=1}, \hat{\hat{\theta}}_{\varepsilon=1})}{\mathcal{L}(\varepsilon = 0, \hat{\mu}_{\varepsilon=0}, \hat{\hat{\theta}}_{\varepsilon=0})}. \quad (6.4)$$

In both the numerator and denominator the likelihood is maximised over all nuisance parameters to obtain the maximum likelihood estimators, $\hat{\mu}$ and $\hat{\hat{\theta}}$ for the respective values of ε . Pseudo-experiments are used for the two hypotheses. For each pseudo-experiment, the auxiliary measurements $\tilde{\theta}$ are randomised around the conditional maximum likelihood estimators $\hat{\hat{\theta}}$ according to their corresponding prior PDFs $\mathcal{A}$. The values of $\hat{\hat{\theta}}$ are obtained from a fit to the observed data assuming $\varepsilon = 0$. The pseudo-experiments are used to obtain the corresponding distributions in q , as well as the p-values, which define the expected and observed sensitivities.

Testing the compatibility with the alternative hypothesis, in which $\varepsilon = 0$ and corresponds to the spin-2 signal plus the backgrounds (noted as 2+B), the p-value is defined as the probability of finding a value of the q distribution equally or less compatible with the alternative model, which is the integral of the 2+B from the median expected of the 0+B distribution till infinite (Figure 6.26a)

$$p_{\text{exp}}(2^+) = P(q \geq q_{\text{exp}(0+B)} | \varepsilon = 0) = \int_{q_{\text{exp}(0+B)}}^{\infty} f(q | \varepsilon = 0) dq. \quad (6.5)$$

Similarly, the expected p-value for the SM hypothesis ($\varepsilon = 1$ corresponding to the 0+B) is the probability of finding a q-value equally or less compatible with the 0+B model. This is calculated via the integral of the 0+B from the median expected of the 2+B distribution to 0 (Figure 6.26a)

$$p_{exp}(0^+) = P(q \geq q_{exp(2+B)} | \varepsilon = 1) = \int_0^{q_{exp(2+B)}} f(q | \varepsilon = 1) dq. \quad (6.6)$$

Finally, for the observed data, the p-value for compatibility with the 2+B hypothesis is defined as the probability of finding a q-value equally or less compatible with the 2+B model, with respect to the one measured in data, assuming the 0+B hypothesis to be true (Figure 6.26b)

$$p_{obs}(2^+) = P(q \geq q_{obs} | \varepsilon = 0) = \int_{q_{obs}}^{\infty} f(q | \varepsilon = 0) dq. \quad (6.7)$$

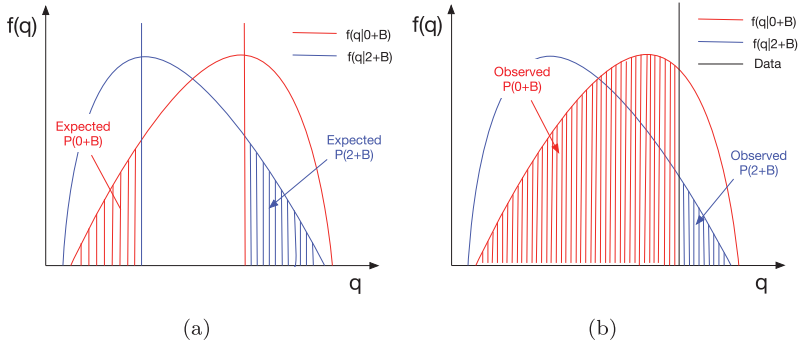


Figure 6.26: (a) The expected $p_{exp}(2^+)$ (blue dashed area) and expected $p_{exp}(0^+)$ (red dashed area). (b) The observed $p_{obs}(2^+)$ (blue dashed area) and observed $p_{obs}(0^+)$ (red dashed area).

When the $p(2^+)$ ($p(0^+)$) values have been obtained, the $1-p(2^+)$ ($1-p(0^+)$) value is the probability of rejecting the 2+B (0+B) hypothesis, assuming that the 0+B (2+B) is true. For example, a p-value of $p(2^+) = 0.05$ corresponds to a 95% rejection probability for the $J^P = 2^+$ hypothesis.

As far as the confidence level is concerned, to exclude an alternative hypothesis in favour of the SM, the confidence level is given by the CL estimator [152]

$$CL_S = \frac{p(ALT)}{1 - p(0^+)}, \quad (6.8)$$

which gives the rejection power of the alternative hypothesis normalised to the compatibility with the SM case.

6.7 Input Variables and Discriminant in the Signal Region

Figures 6.27 and 6.28 show the input variables distributions in the signal region. The spin-0 (spin-2) signal is stacked on top of the backgrounds in the left- (right-) hand side plots. In each case, the signal is normalised to the Standard Model cross section with signal strength of $\hat{\mu} = 1$. In addition, the normalisation of the background processes, which is taken from the control regions, is pre-fit. Similarly, Figures 6.29 and 6.30 show the BDT distribution in the signal region for the spin-2 study. BDT₀ corresponds to the training using the spin-0 signal, while BDT₂ is using the spin-2 signal with $f_{q\bar{q}} = 25\%$. In a similar way, BDT₃, BDT₄, BDT₅ and BDT₆ correspond to a training that uses the spin-2 signal with $f_{q\bar{q}}$ fractions 100%, 75%, 50%, and 0% respectively. Figure 6.31 shows the BDT output distributions for the spin-1 study. A good agreement between data and Monte Carlo can be observed in those distributions once the signal is included.

Finally, Figure 6.32 shows the two-dimensional distribution of the BDT₀×BDT₂ space for the spin-2 training for the two signals, background and data. In addition, the corresponding transformation into the one-dimensional histogram which is used for the final fit is shown. Similar distributions for the spin-1 study are shown in Figure 6.33.

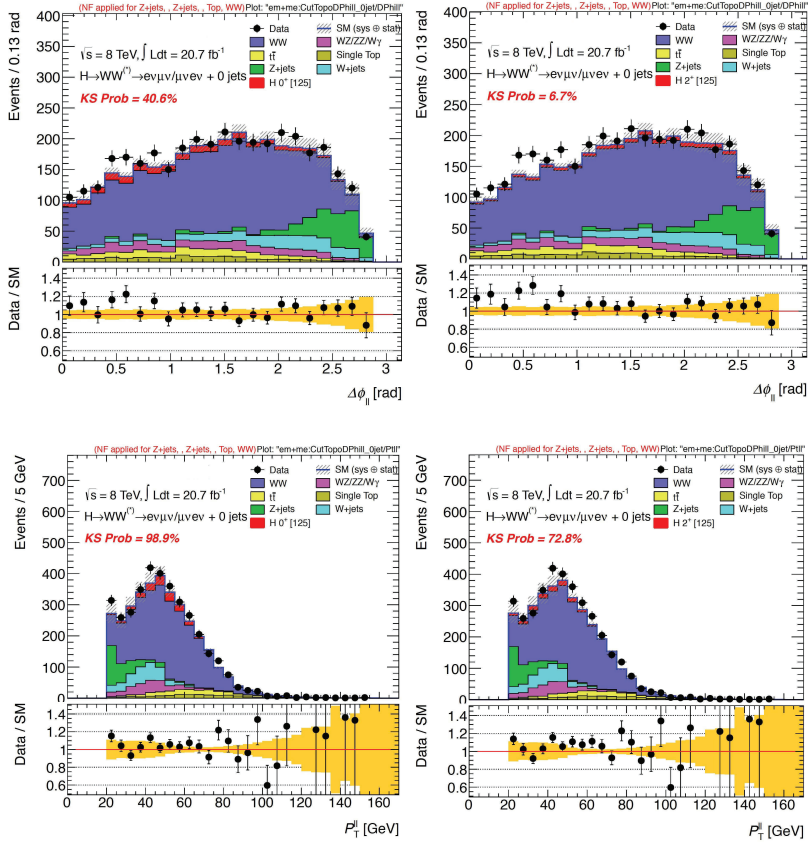


Figure 6.27: Pre-fit $\Delta\phi_{\ell\ell}$ and $P_T^{\ell\ell}$ distributions for the $e\mu$ and μe channels combined after the $\Delta\phi_{\ell\ell}$ selection requirement. The signal shown for $m_H = 125$ GeV under the 0^+ (left) and 2^+ (right) hypotheses. The ratio below each plot compares the data to the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band. An excess in data is observed in the regions where the SM Higgs signal is expected.

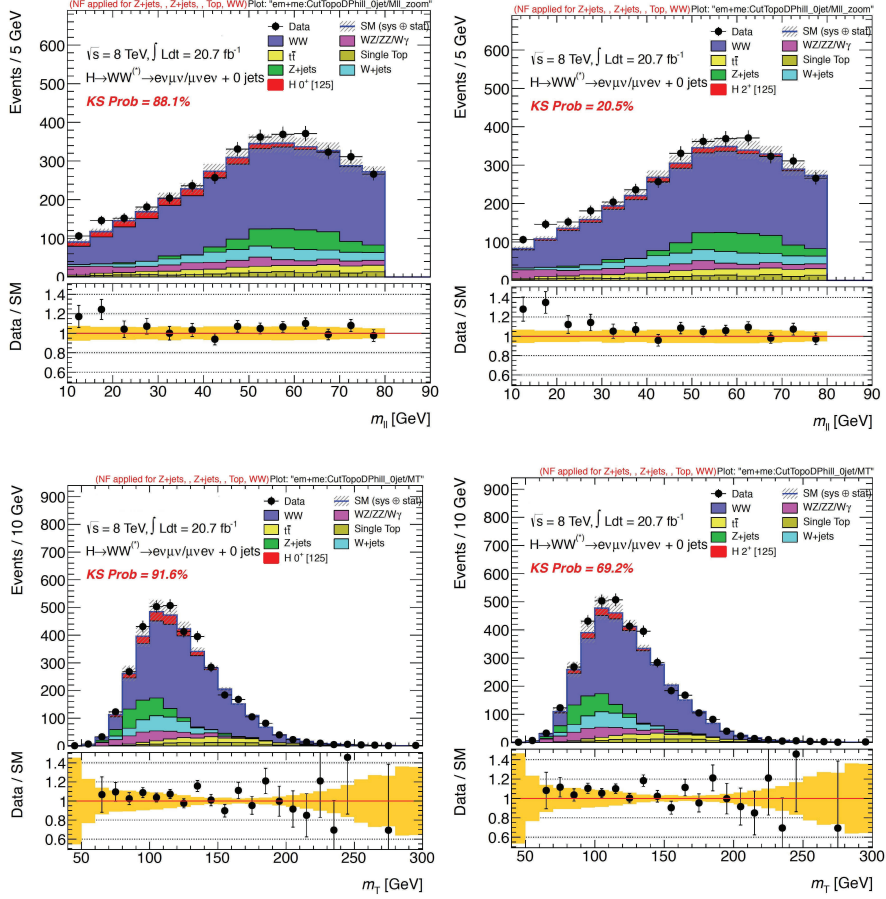


Figure 6.28: Pre-fit $m_{\ell\ell}$ and m_T distributions for the $e\mu$ and μe channels combined after the $\Delta\phi_{\ell\ell}$ selection requirement. The signal shown for $m_H = 125$ GeV under the 0^+ (left) and 2^+ (right) hypotheses. The ratio below each plot compares the data to the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band. An excess in data is observed in the regions where the SM Higgs signal is expected.

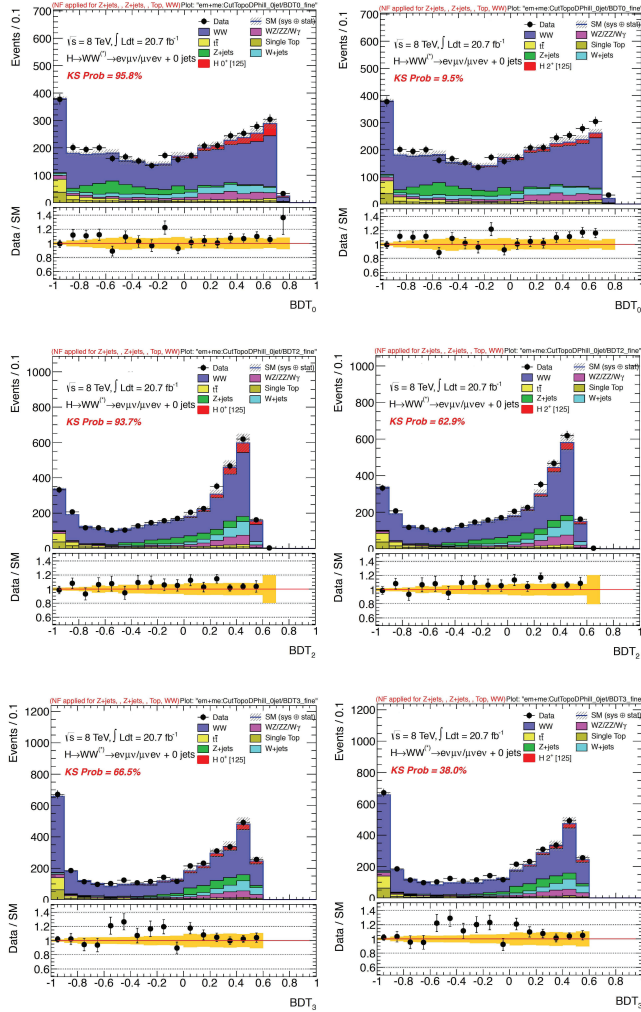


Figure 6.29: Pre-fit BDT output distributions for the $e\mu$ and μe channels combined after the $\Delta\phi_{\ell\ell}$ selection requirement. The signal is shown for $m_H = 125$ GeV for the 0^+ (left) and 2^+ (right) hypotheses stacked on top of the background estimates. BDT_0 corresponds to the 0^+ training, BDT_2 corresponds to the 2^+ training with $f_{q\bar{q}} = 25\%$ and BDT_3 corresponds to the 2^+ training with $f_{q\bar{q}} = 100\%$. The ratio below each plot compares the data to the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band. An excess in data is observed in the regions where the SM Higgs signal is expected.

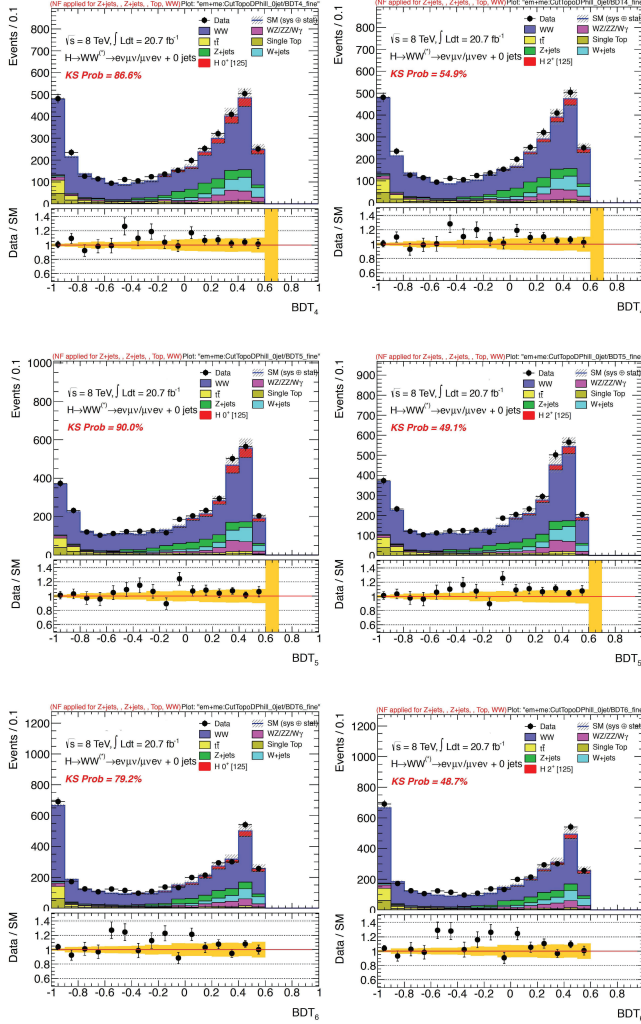


Figure 6.30: Pre-fit BDT output distributions for the $e\mu$ and μe channels combined after the $\Delta\phi_{\ell\ell}$ selection requirement. The signal is shown for $m_H = 125$ GeV for the 0^+ (left) and 2^+ (right) hypotheses stacked on top of the background estimates. BDT₄ corresponds to the 2^+ training with $f_{q\bar{q}} = 75\%$, BDT₅ corresponds to the 2^+ training with $f_{q\bar{q}} = 50\%$ and BDT₆ corresponds to the 2^+ training with $f_{q\bar{q}} = 0\%$. The ratio below each plot compares the data to the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty. An excess in data is observed in the regions where the SM Higgs signal is expected.

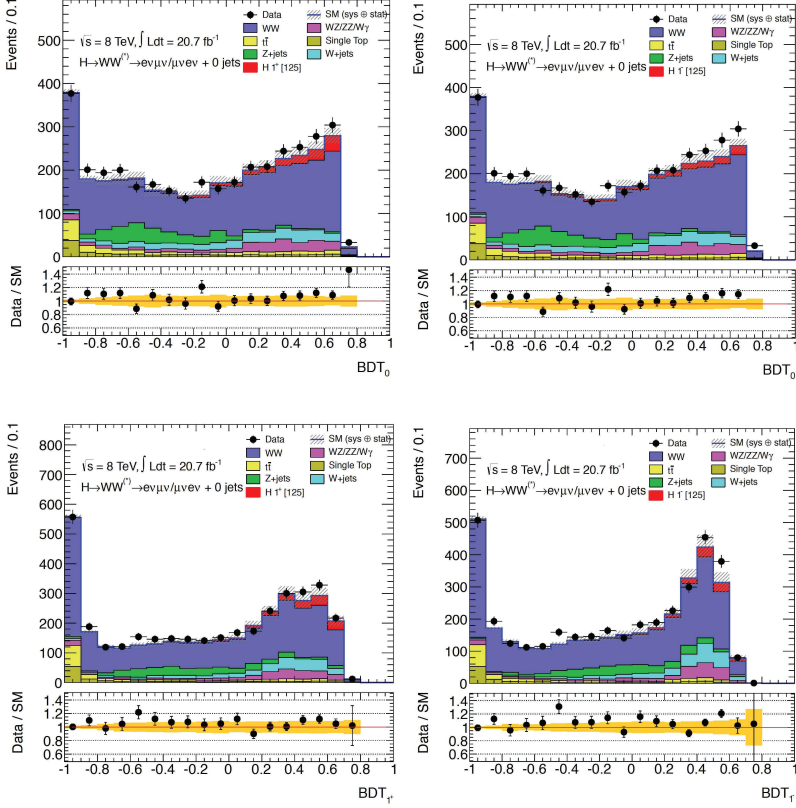


Figure 6.31: Pre-fit BDT output distributions for the $e\mu$ and μe channels combined after the $\Delta\phi_{\ell\ell}$ selection requirement. The signal is shown for $m_H = 125$ GeV for the 1^+ (left) and 1^m (right) hypotheses stacked on top of the background estimates. BDT_0 corresponds to the 0^+ training, BDT_1 corresponds to the 1^+ (left) or 1^- (right) training. The ratio below each plot compares the data to the background expectation. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band. An excess in data is observed in the regions where the SM Higgs signal is expected.

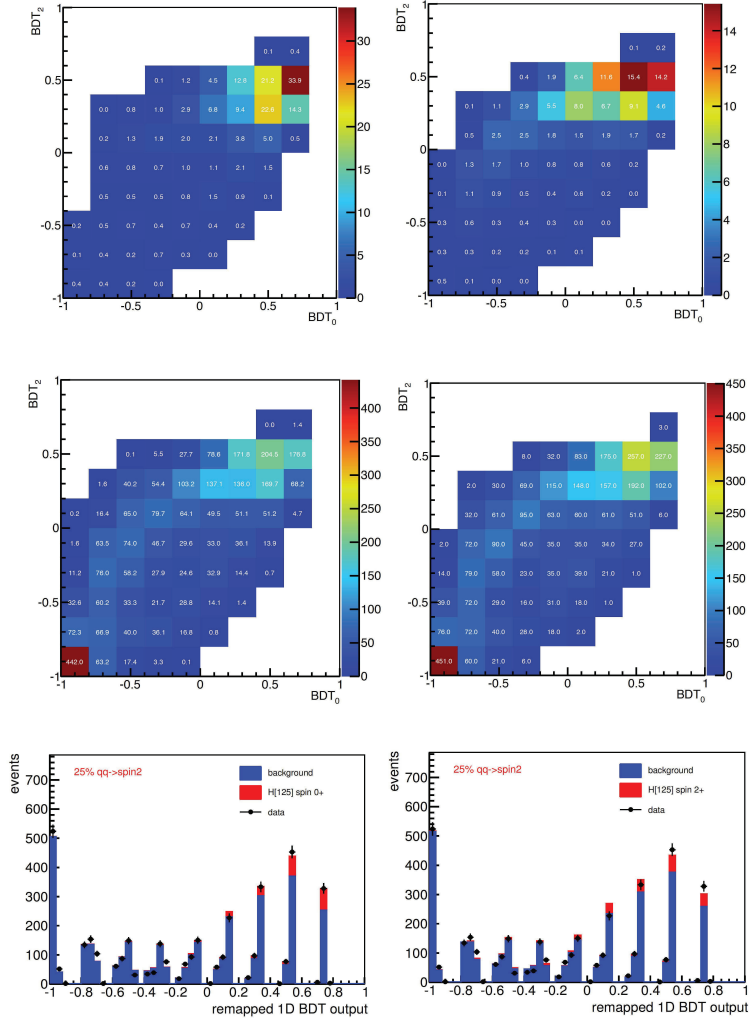


Figure 6.32: 2D distributions of the BDT0×BDT2 space for $f_{q\bar{q}} = 25\%$ spin-2 training (top two rows) for the spin-0 signal (top left) and the spin-2 signal (top right), as well as for the background (middle left) and the data (middle right). The bottom row shows the unrolled (remapped) distributions as they are used in the fit for the 0^+ signal (left) and the 2^+ signal (right) stacked on top of the background distributions. In the unrolled distributions the signal is scaled using the fitted $\hat{m}_u$ -values and the WW , $Z/\gamma^* + \text{jets}$ background processes are scaled using the post fit event yields.

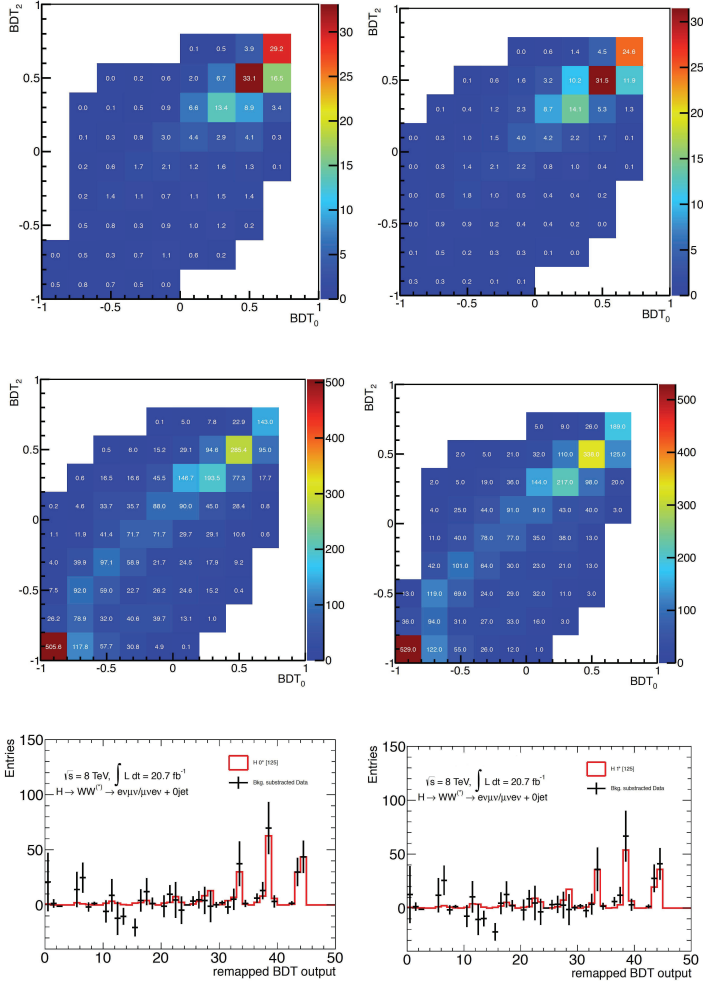


Figure 6.33: Two-dimensional distributions of the BDT0×BDT2 space for the spin-1⁺ training (top two rows) for the spin-0 signal (top left) and the spin-1⁺ signal (top right), as well as for the background (middle left) and the data (middle right). The bottom row shows the unrolled (remapped) distributions as they are used in the fit for the 0⁺ signal (left) and the 1⁺ signal (right) stacked on top of the background distributions. In the unrolled distributions the signal is scaled using the fitted $\hat{\mu}$ -values and the WW , $Z/\gamma^* + \text{jets}$ background processes are scaled using the post fit event yields.

6.8 Results

The compatibility of the different spin hypotheses with the observed data is evaluated using the prescription described in Section 6.6. In addition, as already discussed, since the shapes and therefore the final result for the spin-2 analysis depends on the $f_{q\bar{q}}$ production fraction, the spin-2 fit is performed at the five working points $f_{q\bar{q}} = 0\%$, 25%, 50%, 75%, 100%, using a different BDT trainings per fraction. The distribution of the test statics, q , for the spin-0 and the five spin-2 working points are shown in Figure 6.34, while Figure 6.35 shows the same q distributions comparing the spin-0 and spin-1 $^\pm$ hypotheses.

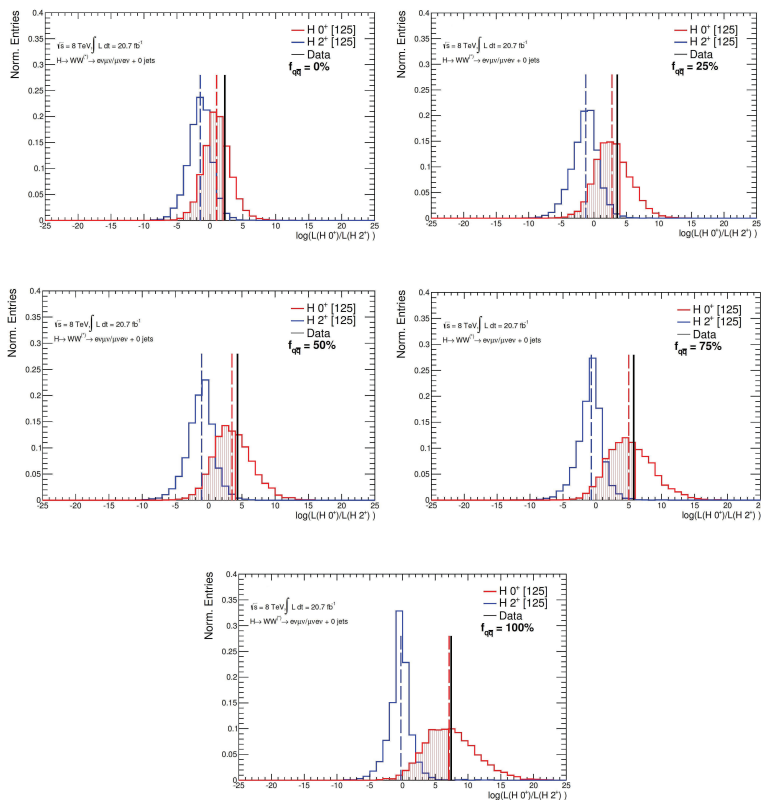


Figure 6.34: Test statistics distributions for the spin-2 analysis for various $f_{q\bar{q}}$ fractions.

The observed rejection of the spin-0 and spin-2 hypotheses is summarised in Table 6.10. In all cases, the Standard Model spin/CP hypothesis is strongly favoured in the observed data. The alternative hypothesis of a spin-2 resonance

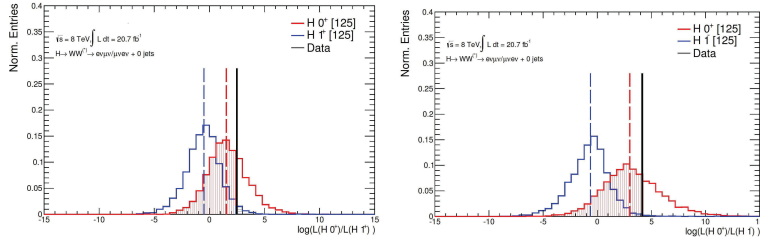


Figure 6.35: Test statistics distributions for the spin-1 analysis.

is excluded with a confidence level of at least 94%, up to 99%, depending on the $f_{q\bar{q}}$ fraction. This result is shown in Figure 6.36, which illustrates the expected and observed limits for the various $f_{q\bar{q}}$ production fraction working points of the spin-2 analysis. The green and yellow bands correspond to the one and two standard deviations contours. Overall, the data are favouring the SM hypothesis and rejecting the alternative spin-2 models at about $\approx 2\sigma$ level.

Similarly, the observed rejection for the spin-0 and the spin-1⁺ and spin-1⁻ hypotheses is summarised in Table 6.11. The SM hypothesis is strongly favoured, with the alternative spin-1⁺ and spin-1⁻ hypotheses excluded in data with a confidence level of 91% and 98%, respectively.

$f_{q\bar{q}}$	$N_{\text{fit}}(0^+)$	$N_{\text{fit}}(2^+)$	Exp. $p_0(0^+)$	Exp. $p_0(2^+)$	Obs. $p_0(0^+)$	Obs. $p_0(2^+)$	1-CL _S (2 ⁺)
100%	270^{+100}_{-80}	110^{+110}_{-90}	0.013	0.005	0.532	0.005	0.9897
75%	250^{+100}_{-80}	170^{+110}_{-100}	0.027	0.005	0.585	0.003	0.9927
50%	250^{+100}_{-80}	230^{+140}_{-100}	0.040	0.012	0.615	0.006	0.9850
25%	260^{+110}_{-80}	260^{+130}_{-110}	0.048	0.019	0.622	0.009	0.9759
0%	260^{+100}_{-80}	320^{+130}_{-110}	0.094	0.064	0.742	0.016	0.9380

Table 6.10: Summary of results for spin-2. The first column represents the different $f_{q\bar{q}}$ production fractions. The second and third columns represent the post-fit event yields for the spin-0 and spin-2 signals. The next two columns represent the expected p_0 -values, and the two following the observed p_0 -values. Finally, the last column gives the confidence levels for the spin-2 hypotheses for all $f_{q\bar{q}}$ fractions. The data are consistent with the SM hypothesis and exclude the spin-2⁺ hypothesis with a confidence level of at least 94%.

The best-fit values for all the nuisance parameters in the binned likelihood are shown in Figure 6.37 for the spin-2 study. In general, no large pulls are observed and the overall distribution is compatible with the couplings analysis. The normalisation factors from the control regions, the detector and theory systematic uncertainties that discussed in the previous sections are shown. Since the test statistics requires two likelihoods to be maximised, depending on the parameter of interest ε , two fits are performed: one for the SM hypothesis

spin	$N_{\text{fit}} (0^+)$	$N_{\text{fit}} (1^\pm)$	Exp. $p_0(0^+)$	Exp. $p_0(1^\pm)$	Obs. $p_0(0^+)$	Obs. $p_0(1^\pm)$	1-CL _S ($1^\pm$)
1 ⁺	253^{+106}_{-81}	230^{+94}_{-74}	0.106	0.077	0.702	0.026	0.9134
1 ⁻	253^{+111}_{-81}	210^{+109}_{-92}	0.064	0.017	0.668	0.006	0.9807

Table 6.11: Summary of results for spin-1. The second and third columns represent the post-fit event yields for the spin-0 and spin-1[±] signals. The next two columns represent the expected p_0 -values, and the two following the observed p_0 -values. Finally, the last column gives the confidence levels for the two spin hypotheses. The data are consistent with the SM hypothesis and exclude the spin-1⁺ (spin-1⁻) hypothesis with a confidence level of at least 91% (98%).

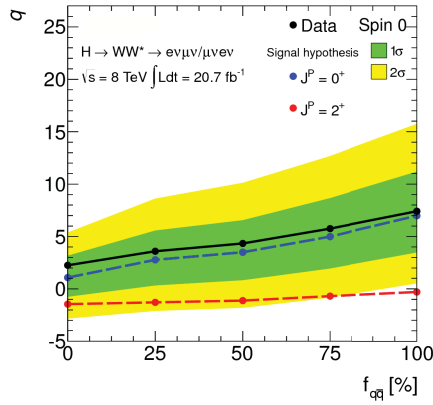


Figure 6.36: One and two standard deviations bands around the observed data as a function of the $f_{q\bar{q}}$ production fraction. The dashed blue and red lines correspond to the expected 0⁺ and 2⁺ hypotheses. The data are rejecting the spin-2 hypothesis for all $f_{q\bar{q}}$ fractions at around 2 σ .

with $\varepsilon = 1$ and one for the alternative, spin-2 hypothesis, with $\varepsilon = 0$. In the distribution for the alternative hypothesis, the W + jets related systematic uncertainty is slightly pulled. This is expected, when the alternative hypothesis is tested against the data, assuming that the data that are consistent of a spin-0 signal.

Similarly, Figures 6.38 and 6.39 show the pulls distributions for the spin-1⁺ and spin-1⁻ hypotheses respectively.

To illustrate the results, Figures 6.40 and 6.41 show the background subtracted plots of the BDT distributions for the spin-2 and spin-1 study, respectively. The background subtracted plots are created by using the post-fit normalisation for the signal (signal strength) and for the backgrounds. Then, from the total observed data histogram the post-fit scaled backgrounds are subtracted and what is left is compared with the scaled signal. Since in the

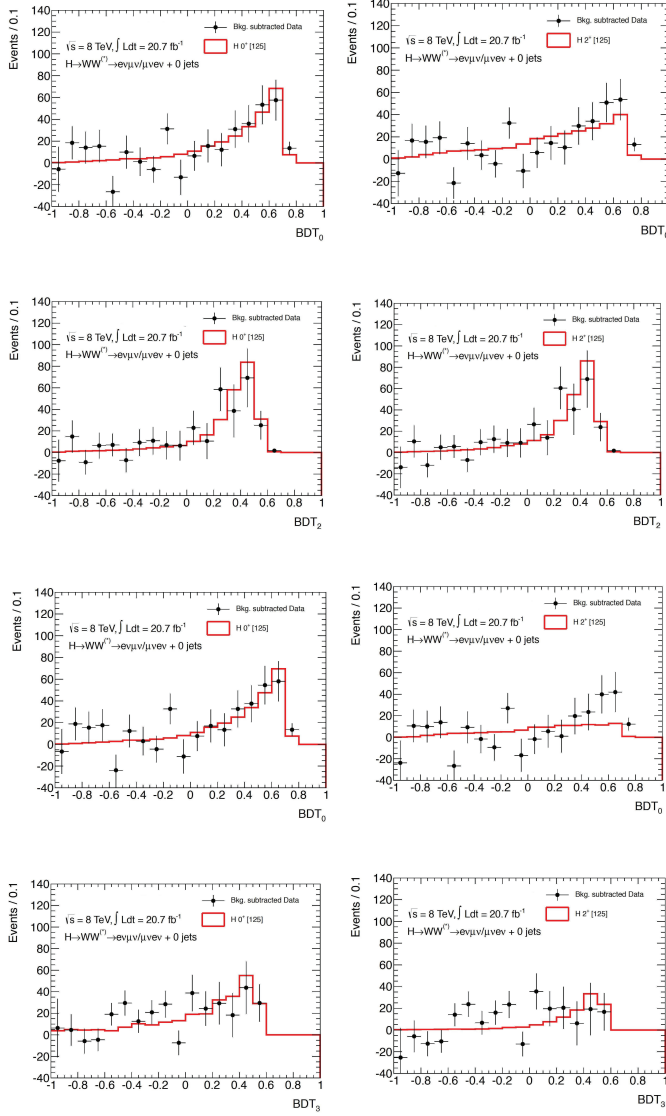


Figure 6.40: Background subtracted distributions for the spin-2 analysis for the $f_{q\bar{q}} = 25\%$ (first and second row) and the $f_{q\bar{q}} = 100\%$ (third and fourth row) fractions. The plots illustrate a test of compatibility between the post-fit scaled data and Monte Carlo signals after subtracting the post-fit scaled background estimation. The data agree better with the SM hypothesis for both fractions.

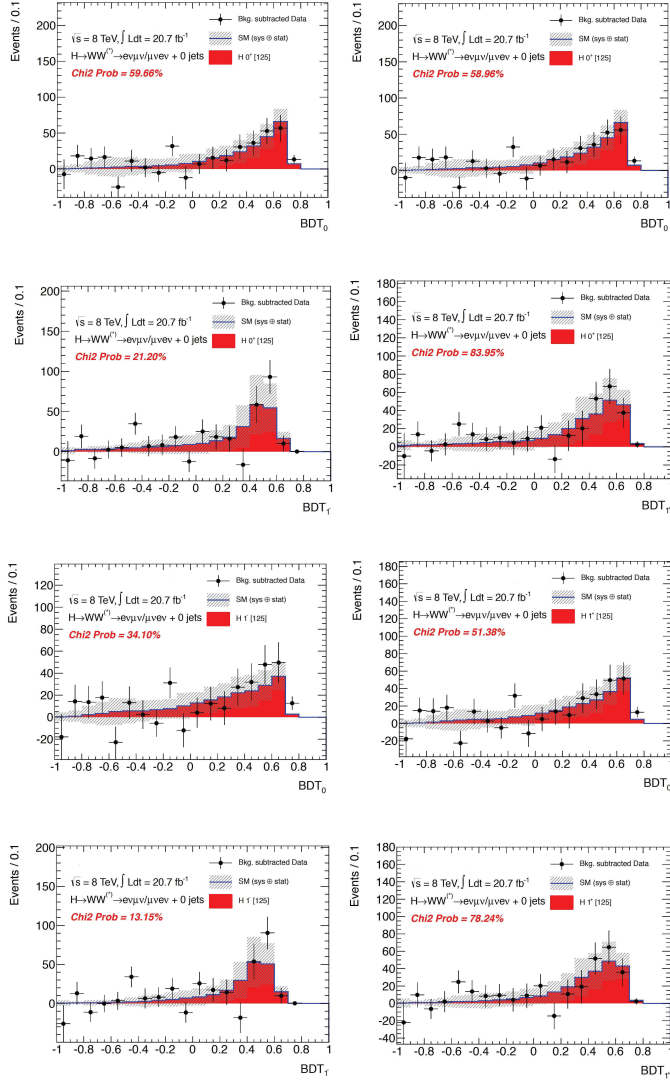


Figure 6.41: Background subtracted distributions for the spin-1 analysis for the 1^- training on the left column and the 1^+ on the right column. The plots illustrate a test of compatibility between the post-fit scaled data and Monte Carlo signals after subtracting the post-fit scaled background estimation. The data agree with the SM hypothesis for both fractions.

6.9 Combination with $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$

The results of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ spin analysis were combined with the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels [119]. As with the BDT approach in the $H \rightarrow WW^*$ decay mode, different analysis strategies are followed in each channel. The $H \rightarrow \gamma\gamma$ channel is using the cosine of the polar angle θ^* of the photons in the Collins-Soper frame [153] and the invariant mass of the diphoton system. In addition, the $H \rightarrow ZZ^*$ channel is also using a BDT approach employing a decision tree trained with the Cabbibo-Maksymowicz variables.

The final result of the combination employs the same statistical interpretation as the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis, using the same test statistics q between the two spin-parity hypotheses. The additional information comes from the likelihood definition which combines the three final states including a product over all channels

$$\mathcal{L}(J^P, \mu, \theta) = \prod_j^{N_{\text{channel}}} \prod_i^{N_{\text{bins}}} P(N_{i,j} | \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta), \quad (6.9)$$

where μ_j represents the signal strength in each channel. Overall, the likelihood is simply the binned product of the Poisson distributions P that correspond to the observation of $N_{i,j}$ events in each bin i of the discriminant observable(s), given that the expectation for the signal is $S_{i,j}^{(J^P)}(\theta)$ and for the background is $B_{i,j}(\theta)$. Finally, some of the nuisance parameters are constrained by auxiliary measurements, which is given by the $\mathcal{A}_i(\theta)$ functions.

For the combined results, all three channels contribute in the spin-2 study, while only $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ contribute in the spin-1 $^\pm$ study. Tables 6.12 and 6.13 show the independent results for the two channels that contribute in the spin-1 analysis. Both $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ are excluding the spin-1 $^+$ alternative hypothesis at more than 90% confidence level independently. The combination of the two, results in an exclusion of the spin-1 $^+$ hypothesis at the level of 99.97%. In addition, the spin-1 $^-$ is excluded at a combined confidence level of 99.73%.

Furthermore, Table 6.14 summarises the results for the spin-2 analysis split over different $f_{q\bar{q}}$ fractions, for all channels contributing to the combination, as well as for the total combined result. The total combined result favours the Standard Model hypothesis, while excluding the spin-2 alternative hypothesis for all $f_{q\bar{q}}$ fractions at a confidence level of at least 99.98%. For the spin-2 study, the robust analysis designed for the $H \rightarrow WW^*$ channel results in being the most sensitive to the exclusion of the alternative hypothesis, with the lowest expected p-values for all the $f_{q\bar{q}}$ points except for the $f_{q\bar{q}} = 0\%$, compared to the other discovery channels where a clean peak of the signal is observed.

Figure 6.42a illustrates the combined result for the expected and observed confidence levels for the $J^P = 2^+$ hypothesis as a fraction of the $f_{q\bar{q}}$ production fraction. The green band represents the $\pm 1\sigma \approx 68\%$ expected exclusion range for the signal assuming $J^P = 0^+$. Finally, Figure 6.42b shows the expected and observed confidence level CL_S for all the spin-parity hypotheses addressed.

After the discovery of the newly Higgs-like resonance, a huge effort was put in determining the spin nature of the boson. The combined ATLAS result presented in this section establishes its spin-0 nature. The $H \rightarrow WW^*$ has a major contribution in most of the aspects of the combined results, despite the fact that the signal resolution is diluted due to the presence of neutrinos and of the large backgrounds in the final state. After this results, and the combined couplings results, the "Higgs-like" bosonic state, was renamed as "Higgs" boson, having spin 0. *But is it **the** Higgs boson?*

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\text{CL}_S (J^P = 1^+)$
$H \rightarrow ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \rightarrow WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

Table 6.12: Table summarising the results for the study of the SM spin/CP hypothesis against the spin- 1^+ alternative one. The results are shown for the individual $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ channels that are included in the combination. The final row of the table shows the combined result. The spin- 1^+ hypothesis is excluded in the data with a confidence level of at least 99%.

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$\text{CL}_S (J^P = 1^-)$
$H \rightarrow ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \rightarrow WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

Table 6.13: Table summarising the results for the study of the SM spin/CP hypothesis against the spin- 1^- alternative one. The results are shown for the individual $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ channels that are included in the combination. The final row of the table shows the combined result. The spin- 1^- hypothesis is excluded in the data with a confidence level of at least 99%.

$H \rightarrow \gamma\gamma$					
$f_{q\bar{q}}$	2 ⁺ assumed Exp. $p_0(J^P = 0^+)$	0 ⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	CL _S ($J^P = 2^+$)
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

$H \rightarrow ZZ^*$					
$f_{q\bar{q}}$	2 ⁺ assumed Exp. $p_0(J^P = 0^+)$	0 ⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	CL _S ($J^P = 2^+$)
100%	0.102	0.082	0.962	0.001	0.026
75%	0.117	0.099	0.923	0.003	0.039
50%	0.129	0.113	0.943	0.002	0.035
25%	0.125	0.107	0.944	0.002	0.036
0%	0.099	0.092	0.532	0.079	0.169

$H \rightarrow WW^*$					
$f_{q\bar{q}}$	2 ⁺ assumed Exp. $p_0(J^P = 0^+)$	0 ⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	CL _S ($J^P = 2^+$)
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048

Combination					
$f_{q\bar{q}}$	2 ⁺ assumed Exp. $p_0(J^P = 0^+)$	0 ⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	CL _S ($J^P = 2^+$)
100%	$3.0 \cdot 10^{-3}$	$8.8 \cdot 10^{-5}$	0.81	$1.6 \cdot 10^{-6}$	$0.8 \cdot 10^{-5}$
75%	$9.5 \cdot 10^{-3}$	$8.8 \cdot 10^{-4}$	0.81	$3.2 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
50%	$1.3 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	0.84	$8.6 \cdot 10^{-5}$	$5.3 \cdot 10^{-4}$
25%	$6.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	0.80	$0.9 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$
0%	$2.1 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	0.63	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$

Table 6.14: Summary result for the exclusion of the 2⁺ hypotheses for all the $f_{q\bar{q}}$ production fractions. The results are shown independently for the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ channels that are included in the combination. The bottom part of the table shows the combined results. The alternative spin-2 hypothesis is excluded in the data with a confidence level larger than 99% for all the $f_{q\bar{q}}$ configurations.

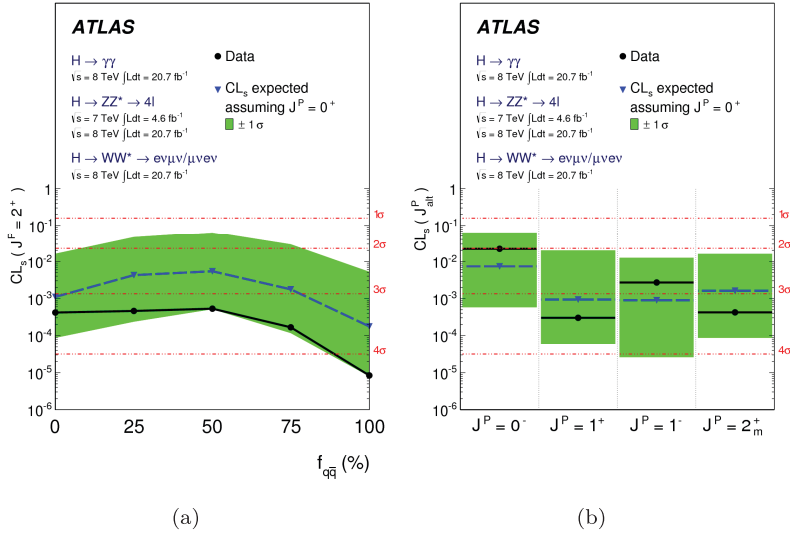


Figure 6.42: (a) Expected (dashed) and observed (solid) confidence CL_S levels for the $J^P = 2^+$ hypotheses as a function of the $f_{q\bar{q}}$ production fraction for the spin-2 particle [119]. (b) The expected (dashed) and observed (solid) confidence level CL_S for all the alternative spin-parity hypotheses assuming a $J^P = 0^+$ signal. In both plots, the green band represents the $\pm 1\sigma \approx 68\%$ CL_S range.

CHAPTER 7

Determining the Spin and CP of the Higgs boson

With respect to the previous chapter, in this one, the 2014 analysis will be discussed. It uses the ATLAS data collected in 2012, summing up to 20.3fb^{-1} . All the latest updates in terms of physics object definition and selection are applied, as it is supposed to be the *legacy* analysis on the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ spin and CP properties studies.

In terms of analysis methods, the CP-mixing study is introduced, which investigates the possibility that the newly discovered resonance is a CP-mixed state. The signal modelling is based on an EFT, as discussed in Chapter 4, which brings new benchmarks to be studied. Furthermore, the spin analysis includes the 1-jet channel. Finally, a more sophisticated binning procedure of the two-dimensional BDT0×BDT2 space is introduced.

This chapter will follow the same structure as the previous one. In the next sub-sections, the BDT analysis applied in the spin and CP study will be discussed, including the validation studies. Followed by the impact of the systematic uncertainties on the analysis, as well as the statistical treatment of the results for both the spin and CP analysis. Finally, the results in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel [124], as well as the combined ATLAS results [154] will be presented.

7.1 Analysis Strategy

After the pre-selection and selection criteria are applied, the analysis is performed based on the strategy which will be explained in the next two following subsections. Two different analyses have been performed in order to study the spin-2 benchmarks and the various spin-0 parity hypotheses includ-

ing the CP mixed ones. The benchmarks that are going to be studied have been described in Chapter 4. Two different BDT training strategies have been developed for the spin and for the CP analyses, they are described in the following.

7.1.1 Spin Analysis

As for the 2013 analysis, two independent BDT classifiers are trained to discriminate between the SM Higgs signal (spin-0⁺) and the background, and another one to discriminate between the alternative signal (spin-2⁺) and the background processes. The responses of the two classifiers are combined in a BDT0 $\times$ BDT2 space. The background processes used in the training include all the Monte Carlo simulated background samples: WW , $t\bar{t}$, single top, WZ , ZZ , $W\gamma$, $W\gamma^*$ and $Z/\gamma^* + \text{jets}$, as well as the data-driven $W + \text{jets}$ background process.

Each of the classifiers is trained twice: once using the even-numbered and once using the odd-numbered events, in order to use the full statistics. Since in this analysis, the 1-jet bin category is included, it is worth to mention that the trainings are performed independently in the 0- and 1-jet category. After their classification, the result in terms of sensitivity is extracted for each jet-bin and the two are combined in one final result. In both jet-bin categories the same set of input variables is used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_T and $p_T^{\ell\ell}$.

For the BDT training phase, a looser selection is applied. For the 0-jet category, the requirements including a selection on $p_T^{\ell\ell} > 20$ GeV, to remove Drell-Yan background, as well as the lower $m_{\ell\ell}$ requirement of 10 GeV, and its upper bound at 100 GeV. On the other hand, for the 1-jet category the signal region is shaped using the same requirements as in 0-jet bin one, but with the addition of the $\Delta\phi_{\ell\ell} < 2.8$ requirement. This requirement is driven by the need to reject the much higher contributions of the $Z + \text{jets}$ background process. In addition, as discussed in Chapter 4, a selection on p_T^H is applied at 125 GeV or 300 GeV, to ensure the unitarity of the model. The requirement on the p_T^H define an individual training. Therefore, the method is trained in both jet-bins once for the $p_T^H < 125$ GeV and once for the $p_T^H < 300$ GeV requirements. Figures 7.1 and 7.2 show the shapes of the input variables for the SM hypothesis and the various benchmarks of the alternative hypothesis in the 0- and 1-jet bin category, respectively. The various benchmark models are discussed in Chapter 4. The difference in shape between the different benchmark models of the alternative hypothesis is more pronounced in the 1-jet bin category.

Table 7.1 shows the parameter settings for the BDT trainings for the spin-2 analysis. The settings are optimised using a similar procedure as described in the previous chapter.

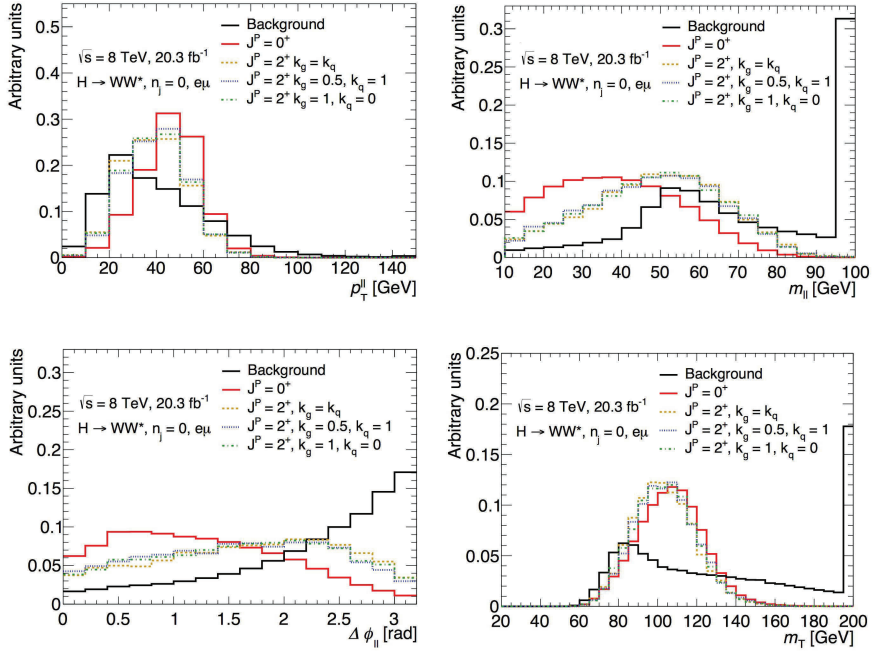


Figure 7.1: $p_T^{\ell\ell}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and m_T distributions for 0^+ (solid red line), 2_m^+ (dashed gold line), $2_{k_g=0.5, k_q=1}^+$ (dashed blue line), $2_{k_g=1, k_q=0}^+$ (dashed green line) signal after the 0-jet requirement. The expected shape for the sum of all backgrounds, including the data-derived $W + \text{jets}$ background is shown (solid black line). The last bin in each plot includes the overflow.

BDT parameter	Value
BoostType	Gradient
MaxDepth	3
NTrees	400
nEventsMin	2% of signal events (about 2000 events)
UseBaggedGrad	true
GradBaggingFraction	0.5
Shrinkage	0.1

Table 7.1: BDT parameters used in the analysis.

7.1.1.1 Performance of Input Variables

For each of the BDT classifiers (BDT0, BDT2) the training algorithm derives the ranking of the input variables. Table 7.2 shows the ranking of the input variables for the trainings that correspond to the SM and the alternative

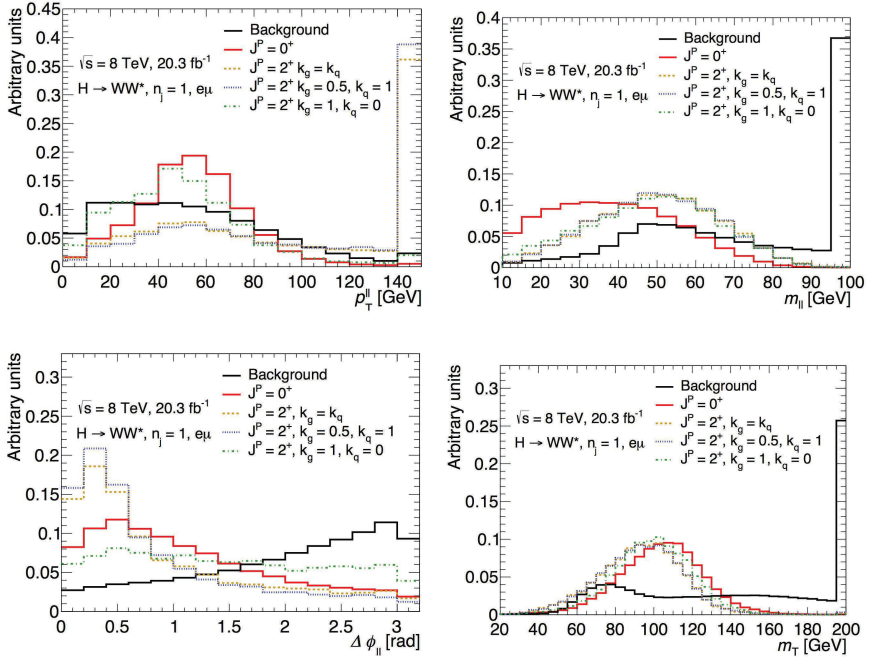


Figure 7.2: $p_T^{\ell\ell}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and m_T distributions for 0^+ (solid red line), 2_m^+ (dashed gold line), $2_{k_g=0.5, k_q=1}^+$ (dashed blue line), $2_{k_g=1, k_q=0}^+$ (dashed green line) signal after the 1-jet requirement. The expected shape for the sum of all backgrounds, including the data-derived W + jets background is shown (solid black line). The last bin in each plot includes the overflow.

hypothesis trainings for the 0- and 1-jet bin categories. The ranking of the variables is similar for all the BDT trainings.

training	ranking 0 jet	ranking 1 jet
BDT0	$\Delta\phi_{\ell\ell}, m_T, m_{\ell\ell}, p_T^{\ell\ell}$	$m_T, m_{\ell\ell}, p_T^{\ell\ell}, \Delta\phi_{\ell\ell}$
BDT2 (2+min)	$m_T, \Delta\phi_{\ell\ell}, m_{\ell\ell}, p_T^{\ell\ell}$	$m_T, m_{\ell\ell}, \Delta\phi_{\ell\ell}, p_T^{\ell\ell}$
BDT2 ($k_g = 1, k_q = 0$), $p_T(H) < 125$ GeV	$m_T, \Delta\phi_{\ell\ell}, m_{\ell\ell}, p_T^{\ell\ell}$	$m_T, \Delta\phi_{\ell\ell}, m_{\ell\ell}, p_T^{\ell\ell}$
BDT2 ($k_g = 1, k_q = 0$), $p_T(H) < 300$ GeV	$m_T, \Delta\phi_{\ell\ell}, m_{\ell\ell}, p_T^{\ell\ell}$	$p_T^{\ell\ell}, m_T, \Delta\phi_{\ell\ell}, m_{\ell\ell}$
BDT2 ($k_g = 0.5, k_q = 1$), $p_T(H) < 125$ GeV	$m_T, m_{\ell\ell}, \Delta\phi_{\ell\ell}, p_T^{\ell\ell}$	$m_T, m_{\ell\ell}, \Delta\phi_{\ell\ell}, p_T^{\ell\ell}$
BDT2 ($k_g = 0.5, k_q = 1$), $p_T(H) < 300$ GeV	$m_T, m_{\ell\ell}, \Delta\phi_{\ell\ell}, p_T^{\ell\ell}$	$p_T^{\ell\ell}, m_T, m_{\ell\ell}, \Delta\phi_{\ell\ell}$

Table 7.2: Ranking of BDT training variables in the 0-jet and 1-jet final states for all BDT trainings. The highest ranked variable is listed first, followed by the second highest and so on.

7.1.1.2 Overtraining Check

The overtraining check is performed on the BDT discriminants to test if they are affected by statistical fluctuations. To quantify this comparison a Kolmogorov-Smirnov test is used. For each spin-2 hypothesis, a KS test is performed on the BDT output distributions from the training and testing samples. A high KS test result indicates that the pair of distributions being compared are in good agreement. For BDT0 and BDT2, in the 2_{min}^+ analysis with universal couplings, the KS probabilities comparing training and testing distributions for signal (and background) are 0.77 (0.32) and 0.95 (0.73), for the 0-jet channel, and 0.76 (0.13) and 0.66 (0.11), for the 1-jet channel, respectively. Similar numbers are retrieved for other spin-2 benchmarks.

7.1.1.3 Modelling of the Input Variables

The modelling of the input variables that are used in the spin analysis is tested in the three control regions that are used for the study. In the background enriched of the WW (both in 0-jet and 1-jet category), the $Z/\gamma^* \rightarrow \tau\tau$ (both in 0-jet and 1-jet category) and the top-quark (in 1-jet category) background process, the Monte Carlo estimation is tested against the data. Figures 7.3 and 7.4 show the spin-analysis input variables in the 0- and 1-jet categories in the WW control region. Similarly, 7.5 and 7.6 show the same distributions in the 0- and 1-jet categories in the $Z/\gamma^* \rightarrow \tau\tau$ control region. Finally, Figure 7.7 shows the input variables in the 1-jet category of the top-quark control region.

7.1.1.4 Input Variables Correlations

The correlations between the input variables in the signal region are used by the BDT to distinguish between signal and background, as well as between signal hypotheses. The SM signal and the alternative spin-2 signal with minimal couplings have been used to study the correlations of the input variables. The scatter plots in Figures 7.8 and 7.9 show the correlations of the input variables in the signal region for the 0-jet bin category. Similarly, Figures 7.10 7.11 show the same distributions in the 1-jet category signal region. As expected the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions are highly correlated, similarly m_T and $p_T^{\ell\ell}$.

To verify that the correlations between the input variables of the BDT are modelled correctly, the data and Monte Carlo distributions of the correlations have been obtained by calculating per event the correlation coefficient

$$C(i) = \frac{(x(i) - \bar{x}) \cdot (y(i) - \bar{y})}{\sigma_x \cdot \sigma_y}, \quad (7.1)$$

where $x(i)$ and $y(i)$ are the values of the variables in the event i , and $\bar{x}$ and $\bar{y}$ the mean values of the variables over all events, with σ_x and σ_y their standard deviations.

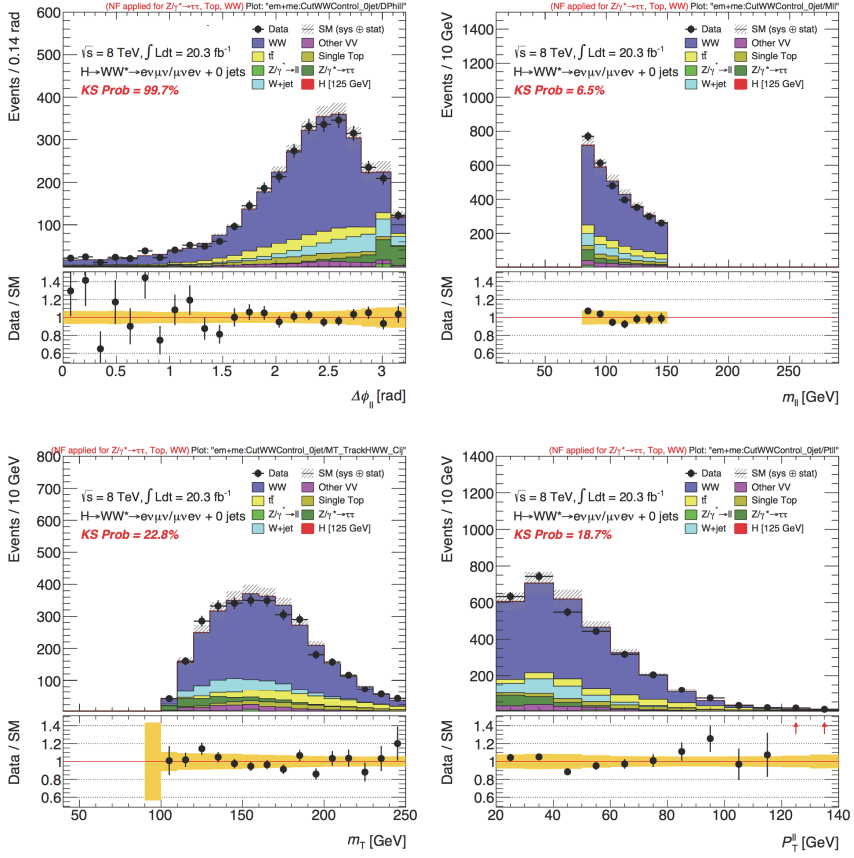


Figure 7.3: The distributions for the input variables of the spin analysis in the WW control region of the 0-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

The correlation coefficients are calculated for the Monte Carlo and data samples in the control regions of the analysis. The results of the coefficients in all control regions are summarised in Table 7.3, where a good agreement between data and Monte Carlo is found for all the combinations among the variables.

In addition to the linear correlation coefficients, the profile plots are shown in Figure 7.12 for the WW control region, in Figure 7.13 for the top and in Figure 7.14 for the $Z/\gamma^* \rightarrow \tau\tau$ control region for data and Monte Carlo. The profile plots are used to display the mean value of the y-axis variable and its error for each bin of the x-axis variable. They are used as an elegant replacement for the two-dimensional scatter plots. As a result, the

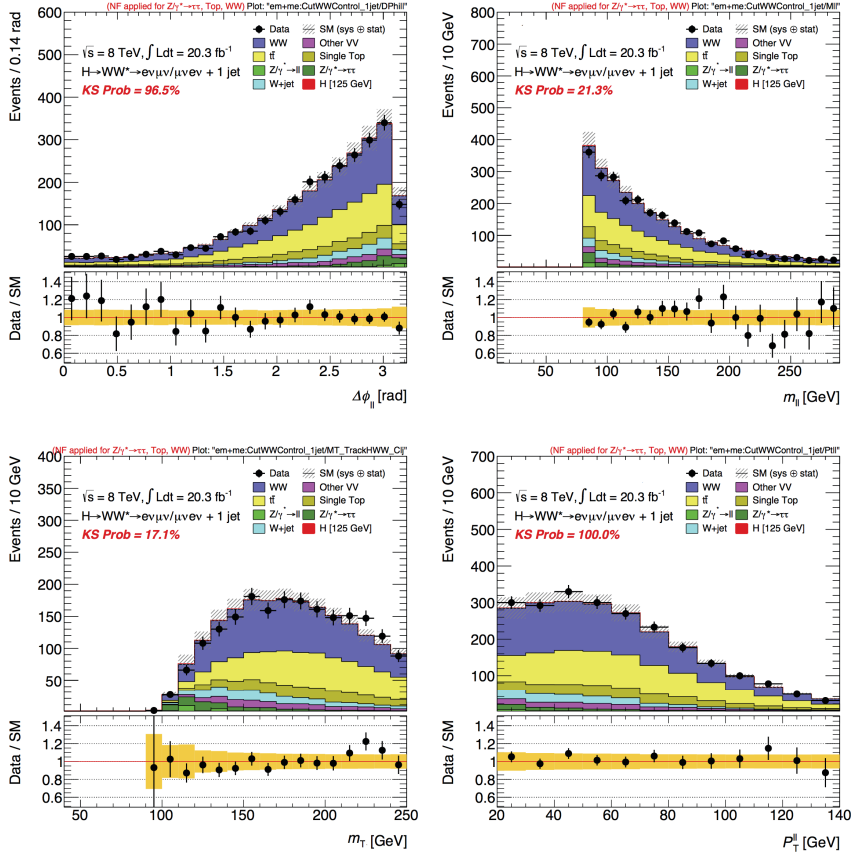


Figure 7.4: The distributions for the input variables of the spin analysis in the WW control region of the 1-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

correlations of the BDT inpt variables are well modelled in Monte Carlo within the uncertainties.

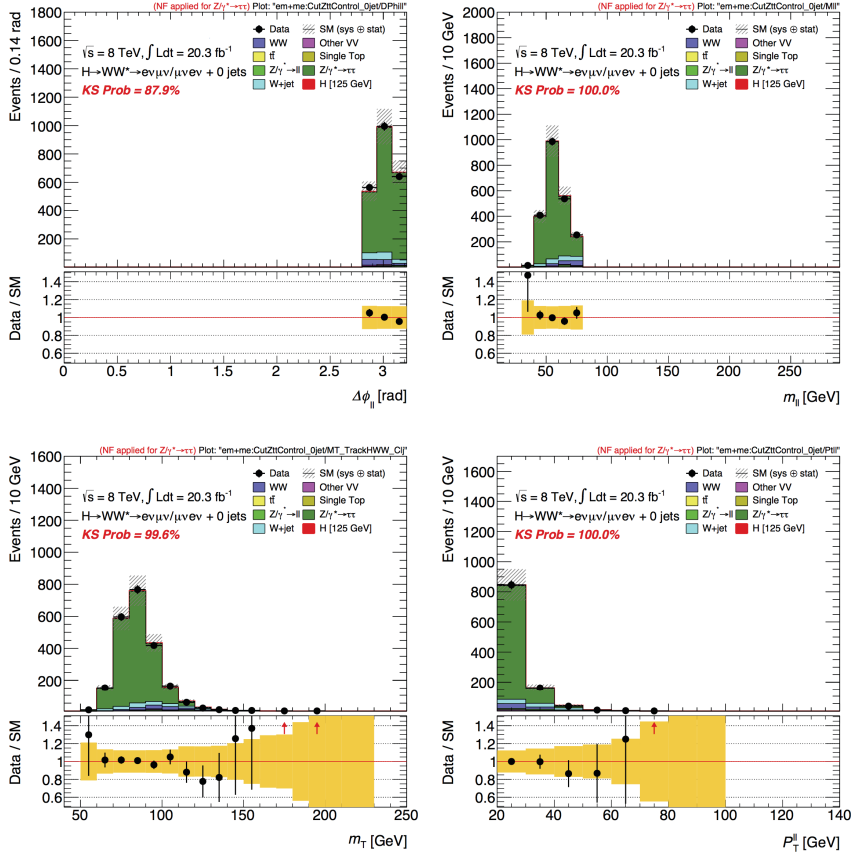


Figure 7.5: The distributions for the input variables of the spin analysis in the $Z/\gamma^* \rightarrow \tau\tau$ control region of the 0-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

	$\Delta\phi_{\ell\ell} m_{\ell\ell}$	$\Delta\phi_{\ell\ell} m_T$	$\Delta\phi_{\ell\ell} p_T^{\ell\ell}$	$m_{\ell\ell} m_T$	$m_{\ell\ell} p_T^{\ell\ell}$	$m_T p_T^{\ell\ell}$
WW 0-jet: data	0.12 ± 0.02	-0.3 ± 0.02	-0.50 ± 0.01	0.54 ± 0.01	0.09 ± 0.02	0.86 ± 0.01
WW 0-jet: bkg	0.10 ± 0.00	-0.35 ± 0.00	-0.50 ± 0.00	0.56 ± 0.00	0.09 ± 0.00	0.84 ± 0.00
WW 1-jet: data	0.18 ± 0.02	0.06 ± 0.02	-0.43 ± 0.02	0.89 ± 0.00	0.22 ± 0.02	0.44 ± 0.02
WW 1-jet: bkg	0.19 ± 0.00	0.06 ± 0.00	-0.44 ± 0.00	0.89 ± 0.00	0.29 ± 0.00	0.51 ± 0.00
Top 1-jet: data	0.49 ± 0.01	0.27 ± 0.01	-0.45 ± 0.01	0.86 ± 0.00	0.12 ± 0.01	0.39 ± 0.01
Top 1-jet: bkg	0.49 ± 0.00	0.29 ± 0.00	-0.46 ± 0.00	0.87 ± 0.00	0.13 ± 0.00	0.35 ± 0.00
$Z\tau\tau$ 0-jet: data	-0.06 ± 0.02	-0.08 ± 0.02	-0.10 ± 0.02	0.83 ± 0.01	0.35 ± 0.02	0.71 ± 0.01
$Z\tau\tau$ 0-jet: bkg	-0.05 ± 0.00	-0.06 ± 0.00	-0.07 ± 0.00	0.83 ± 0.00	0.35 ± 0.00	0.70 ± 0.00
$Z\tau\tau$ 1-jet: data	0.22 ± 0.02	0.28 ± 0.02	-0.80 ± 0.01	0.77 ± 0.01	0.08 ± 0.02	0.03 ± 0.02
$Z\tau\tau$ 1-jet: bkg	0.23 ± 0.00	0.28 ± 0.00	-0.79 ± 0.00	0.75 ± 0.00	0.10 ± 0.00	0.06 ± 0.00

Table 7.3: Mean values of the correlation distributions in the WW , top and $Z\tau\tau$ control regions.

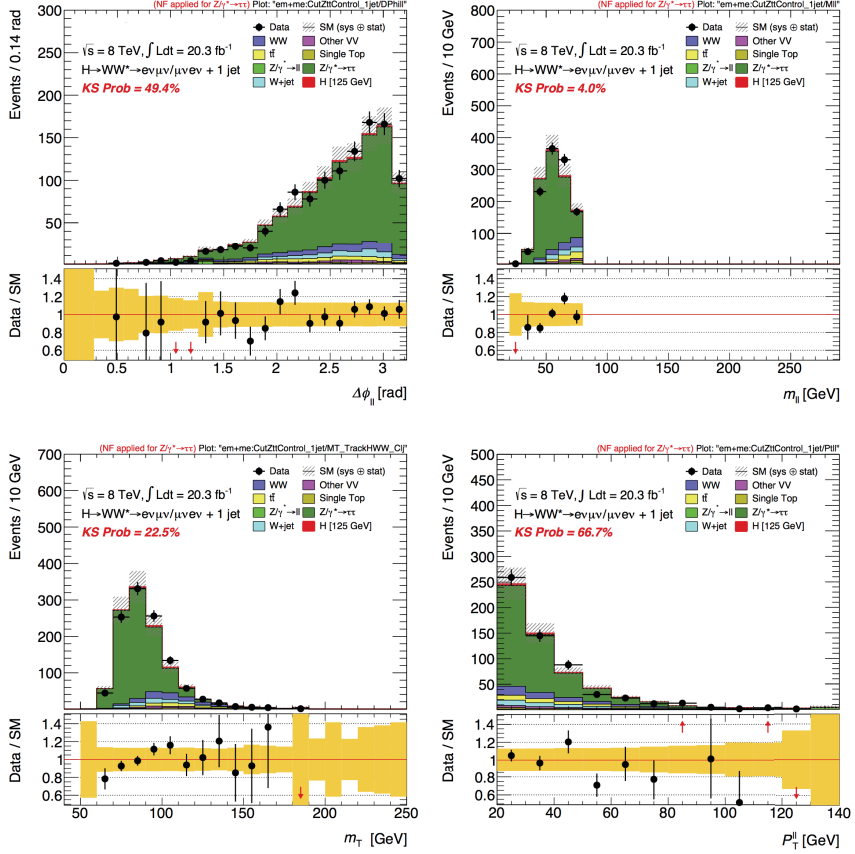


Figure 7.6: The distributions for the input variables of the spin analysis in the $Z/\gamma^* \rightarrow \tau\tau$ control region of the 1-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

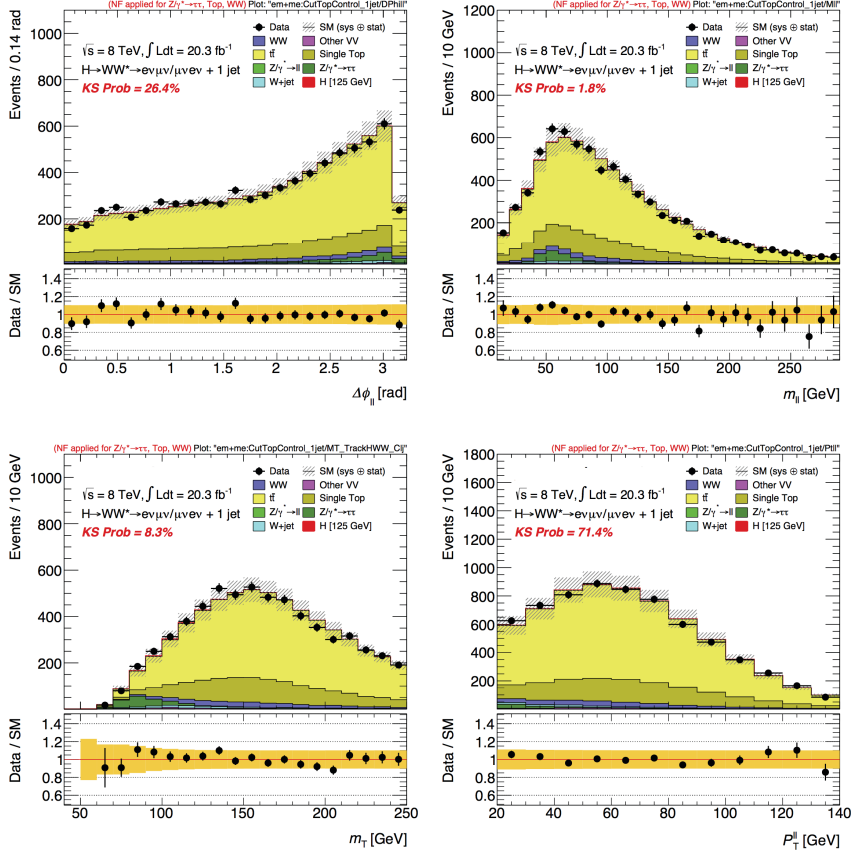


Figure 7.7: The distributions for the input variables of the spin analysis in the top-quark control region of the 1-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

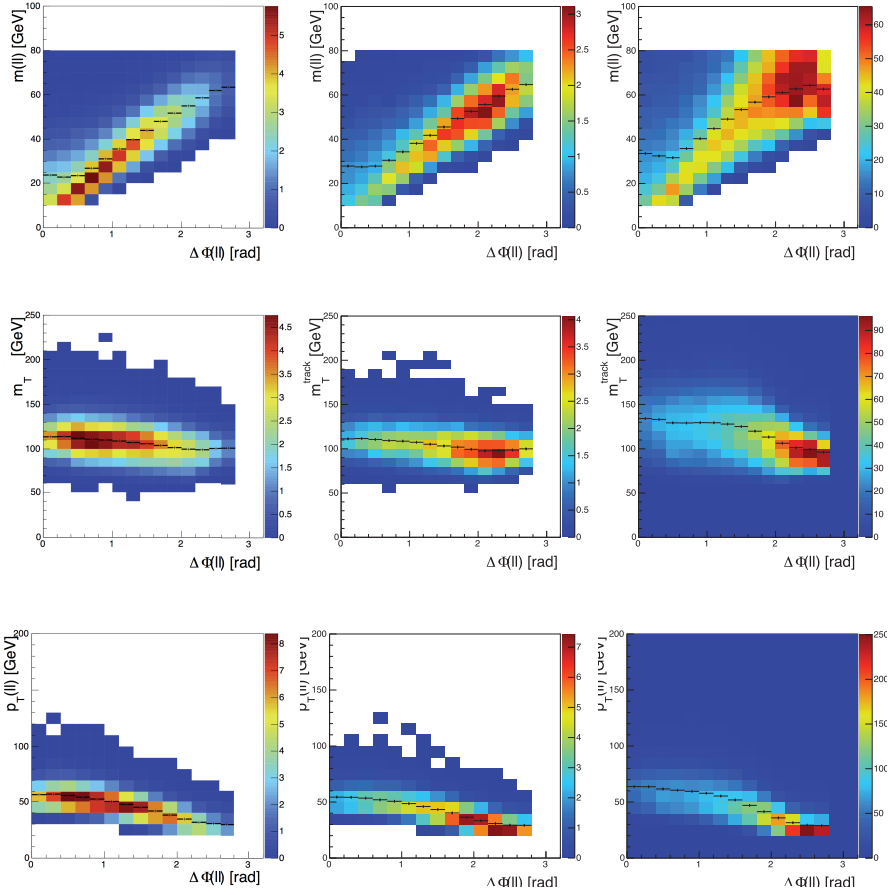


Figure 7.8: Scatter plots for pairs of BDT input variables acquired by simulation for the SM Higgs signal (left), a spin-2 resonance with universal couplings (middle) and the backgrounds (right) in the signal region for the 0-jet channel.

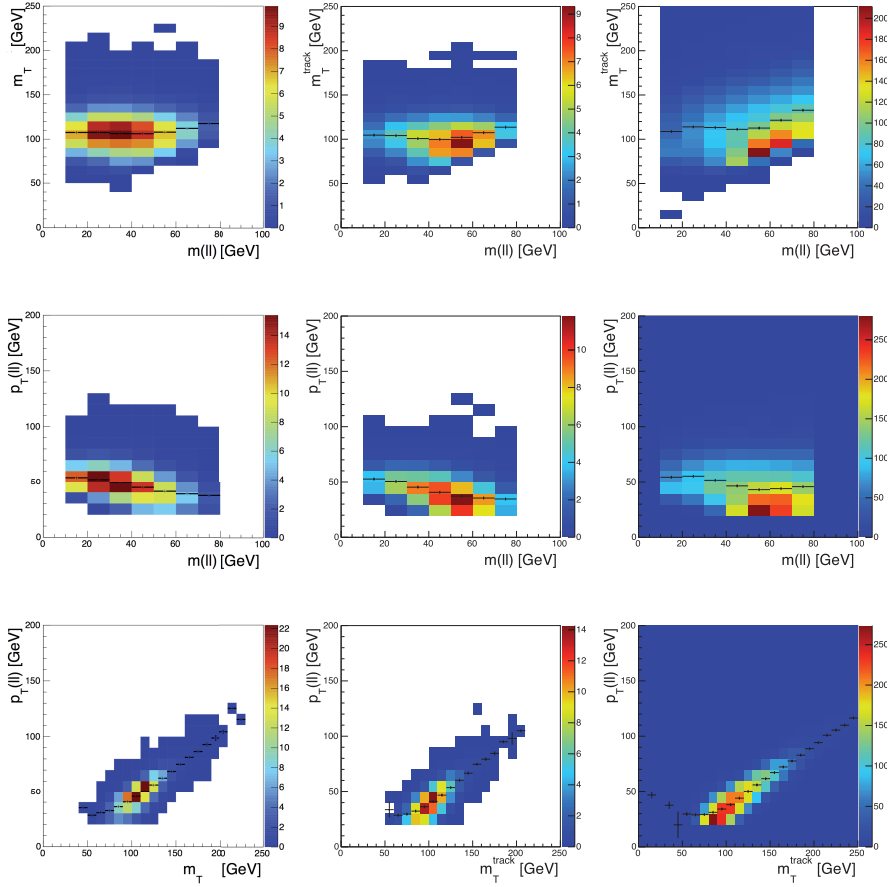


Figure 7.9: Scatter plots for pairs of BDT input variables acquired by simulation for the SM Higgs signal (left), a spin-2 resonance with universal couplings (middle) and the backgrounds (right) in the signal region for the 0-jet channel.

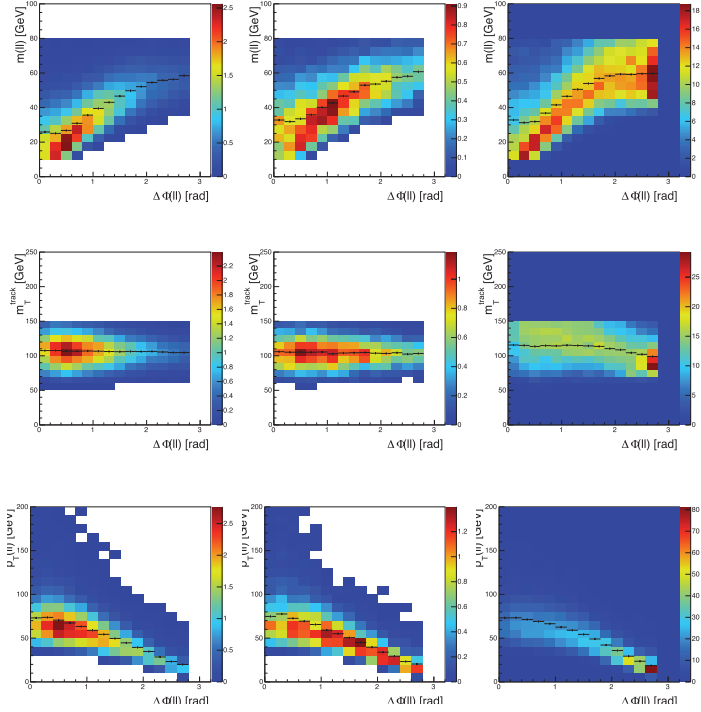


Figure 7.10: Scatter plots for pairs of BDT input variables acquired by simulation for the SM Higgs signal (left), a 2_m^+ resonance with universal couplings (middle) and the backgrounds (right) in the signal region for the 1-jet channel.

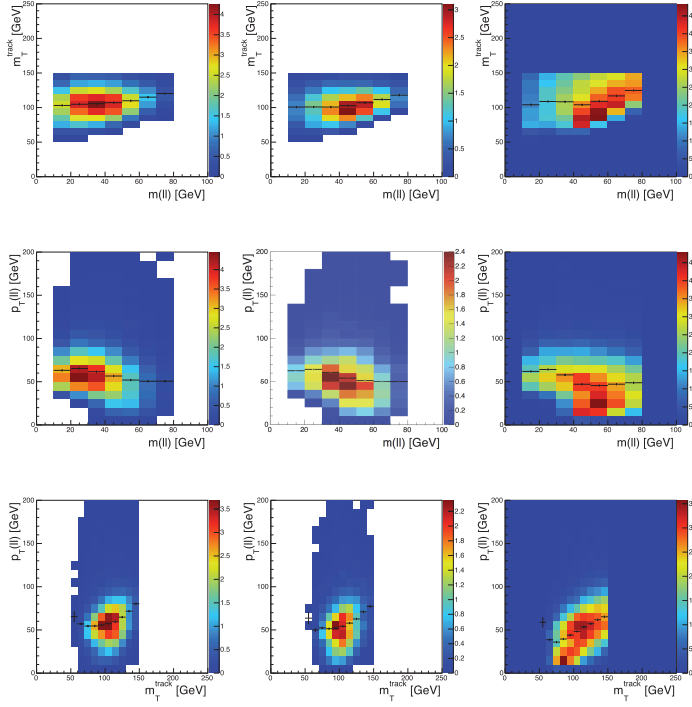


Figure 7.11: Scatter plots for pairs of BDT input variables acquired by simulation for the SM Higgs signal (left), a 2_m^+ resonance with universal couplings (middle) and the backgrounds (right) in the signal region for the 1-jet channel.

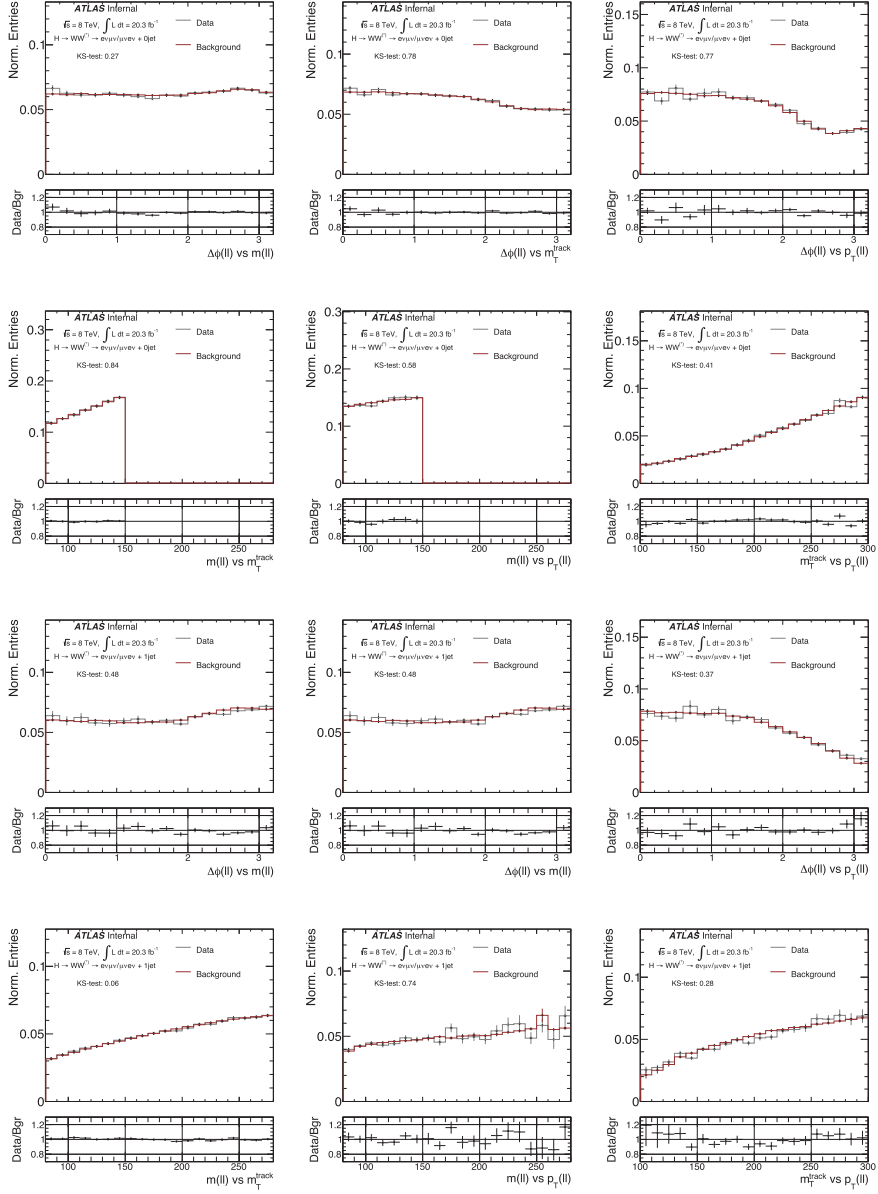


Figure 7.12: Profile plots in the WW control region for pairs of BDT input variables for data and MC backgrounds superimposed. The first two rows show the plots in 0-jet and the last two rows in 1-jet. The ratio below each plot shows the agreement of the data to the background expectation. Error bars include statistical uncertainty.

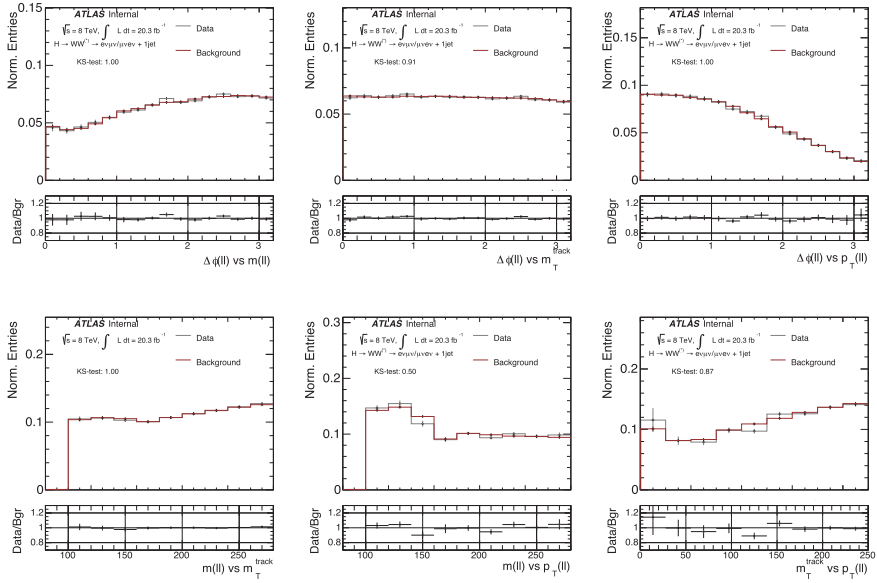


Figure 7.13: Profile plots in the top control region with 1-jet for pairs of BDT input variables for data and MC backgrounds superimposed. The ratio below each plot shows the agreement of the data to the background expectation. Error bars include statistical uncertainty.

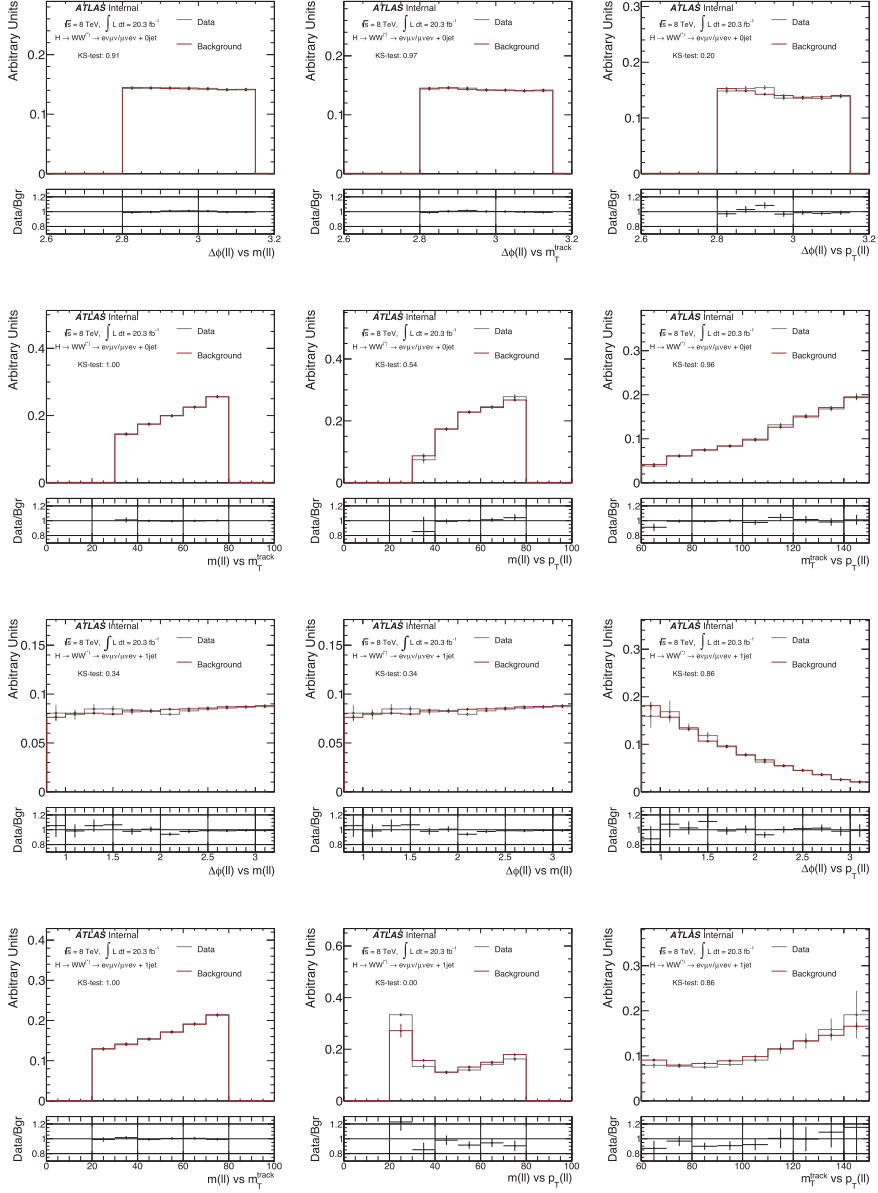


Figure 7.14: Profile plots in the $Z/\gamma^* \rightarrow \tau\tau$ control region for pairs of BDT input variables for data and MC backgrounds superimposed. The first two rows show the plots in 0-jet and the last two rows in 1-jet. The ratio below each plot shows the agreement of the data to the background expectation. Error bars include statistical uncertainty.

7.1.1.5 Modelling of the BDT Discriminant

Figures 7.15 and 7.16 show the BDT output distributions in the WW control region for the 0- and 1-jet bin category, respectively. Similarly, Figures 7.17 and 7.18 show the same distributions in the $Z/\gamma^* \rightarrow \tau\tau$ control region for the 0- and 1-jet bin category, respectively. Figure 7.19 shows the BDT0 and BDT2 distributions in the top control region for the 1-jet category. For all distributions, the SM Higgs signal with $m_H = 125$ GeV is stacked on top of the background estimate. No significant discrepancy between data and Monte Carlo expectation is observed.

Finally, in the signal region, the shapes of the BDT0 and BDT2 for all the benchmark models are shown in Figures 7.20, 7.21, 7.22 for the $p_T^H < 300$ GeV selection and in Figures 7.23, 7.24 for the $p_T^H < 125$ GeV one. The dashed line corresponds to the alternative signal hypothesis in each plot.

7.1.1.6 Training of one of the SM backgrounds against other SM backgrounds

However, as it was mentioned also in the previous chapter, since the background events are all accumulated close to the -1 background-like -1 bin of the BDT discriminant, a more precise test for the modelling should be made. Therefore, a training of the WW background process against the remaining backgrounds is performed in the 0- and 1-jet category. The training parameters are identical to the nominal training in the signal region, with the exception of the $m_{\ell\ell} < 100$ GeV requirement which is dropped and no signal is used for the training. Then the BDT output distribution of this training is plotted in the WW control region. These distributions are shown in Figure 7.25. The data are compared to the background expectation and are well within the statistical and systematic uncertainties. Therefore, no modelling issue is found in the WW control region.

The same procedure is followed for the top-quark control region in the 1-jet category. Since the inclusion of the 1-jet category in the analysis, the top-quark background is dominant in this category, and the modelling in terms of the normalisation and the shape becomes important. Therefore, the same BDT as described above is trained now with the top-quark background process against the remaining backgrounds. The output is plotted in the top-quark control region of the 1-jet category. This distribution is shown in Figure 7.26, where the agreement of the data with the background expectation is tested. The distributions agree well within the statistical and systematic uncertainties. Therefore, no modelling issues have been observed for the BDT output distribution.

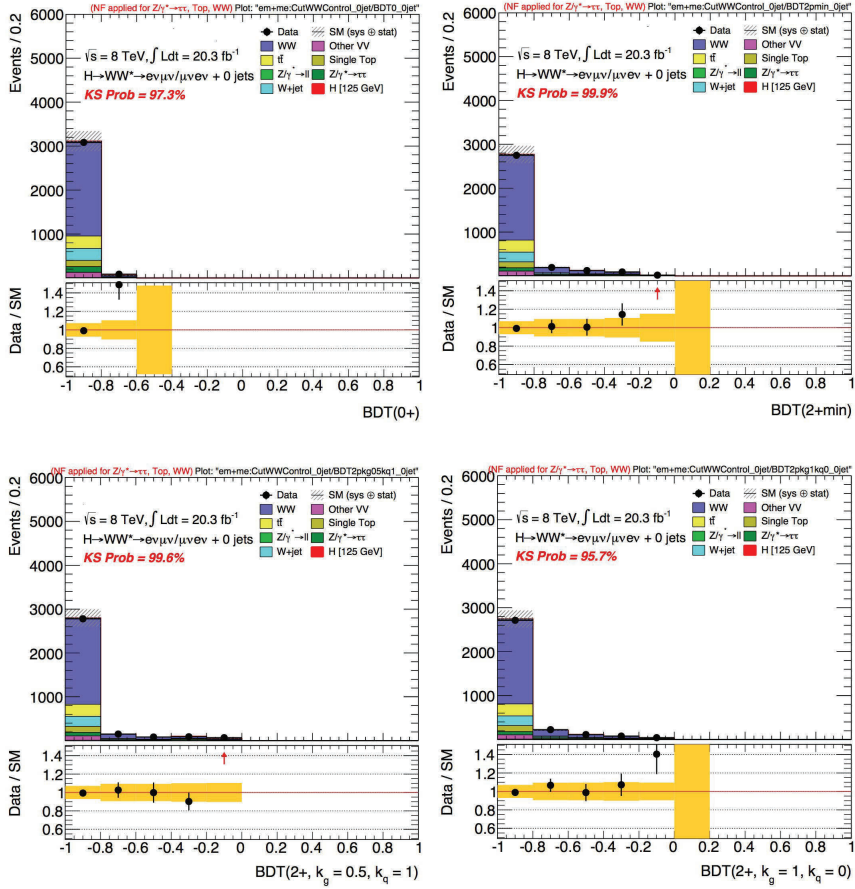


Figure 7.15: The BDT0 and BDT2 output distributions for different benchmark models in the WW control region of 0-jet bin category. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

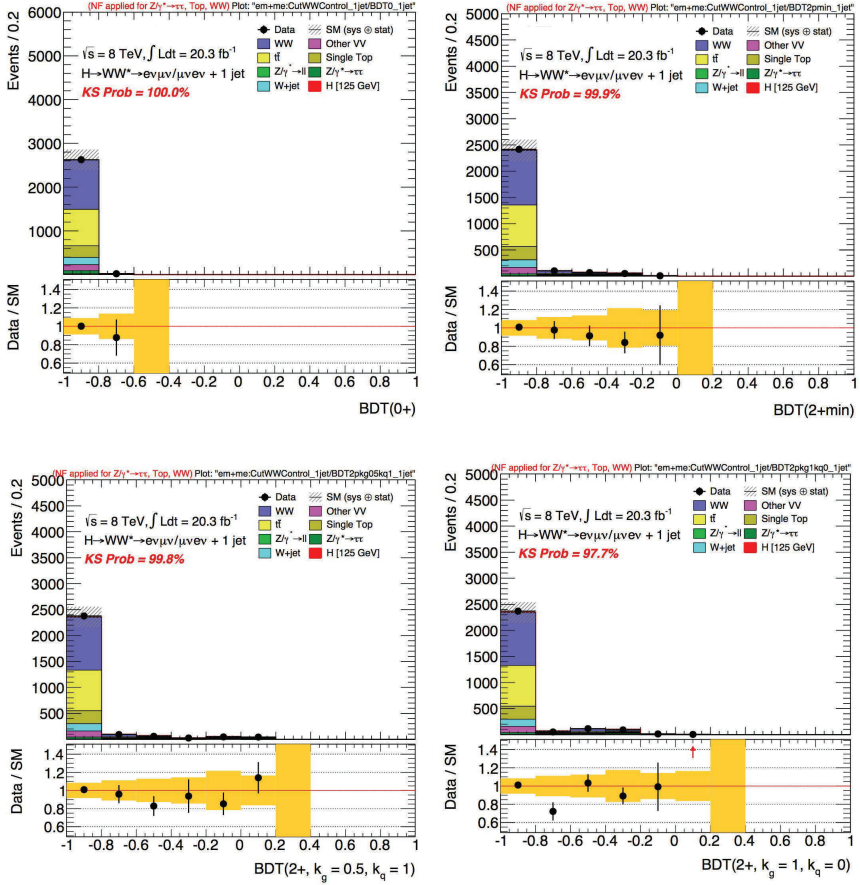


Figure 7.16: The BDT0 and BDT2 output distributions for different benchmark models in the WW control region of 1-jet bin. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

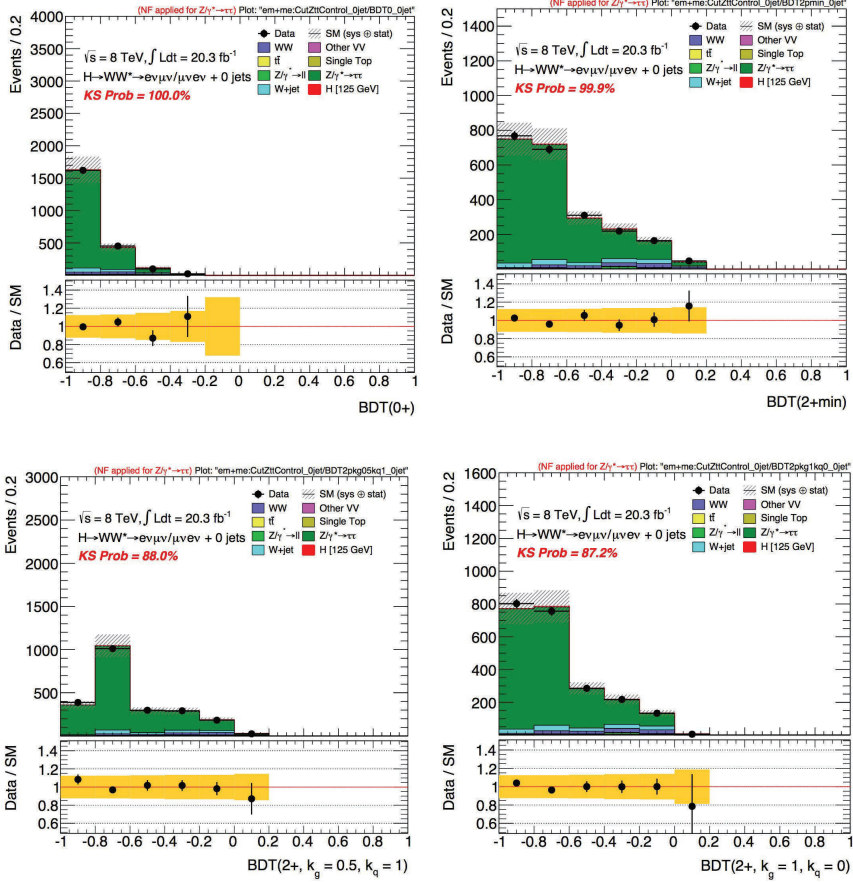


Figure 7.17: The BDT0 and BDT2 output distributions for different benchmark models in the $Z/\gamma^* \rightarrow \tau\tau$ control region of 0-jet bin category. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

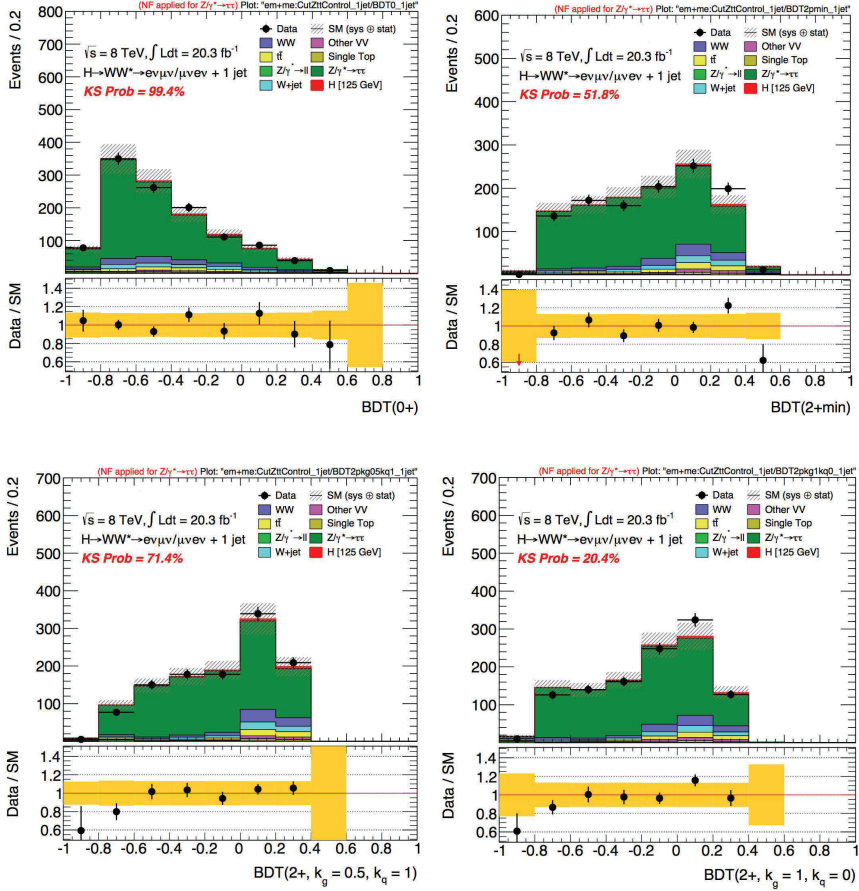


Figure 7.18: The BDT0 and BDT2 output distributions for different benchmark models in the $Z/\gamma^* \rightarrow \tau\tau$ control region of 1-jet bin. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

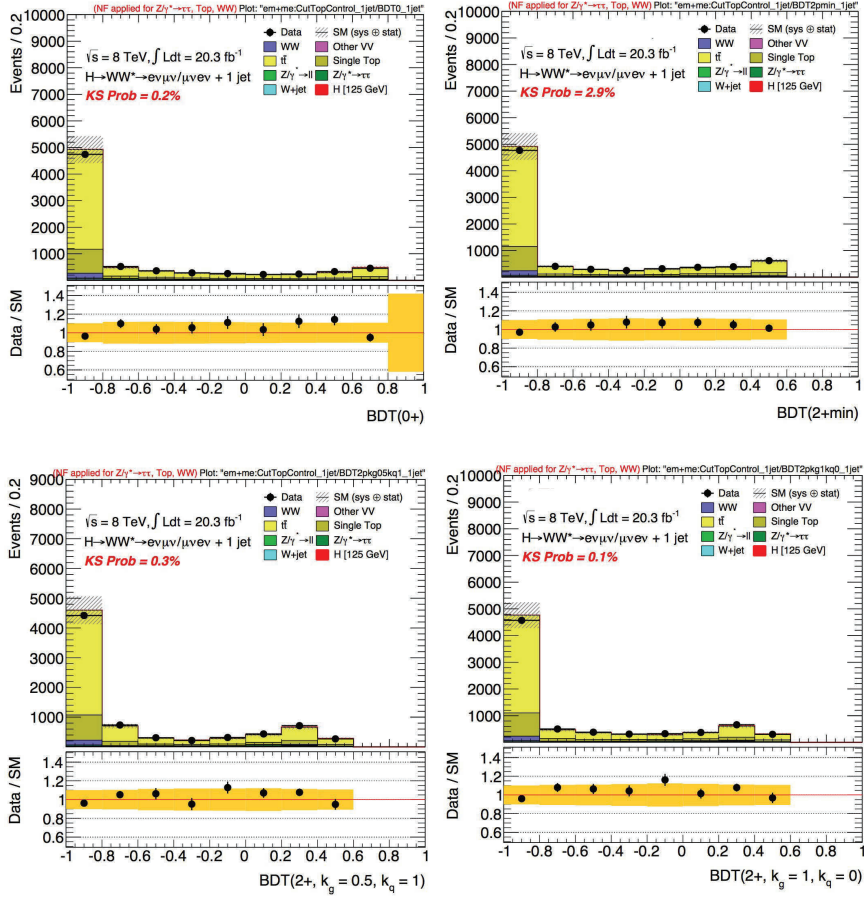


Figure 7.19: The BDT0 and BDT2 output distributions for different benchmark models in the top-quark control region of 1-jet bin. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

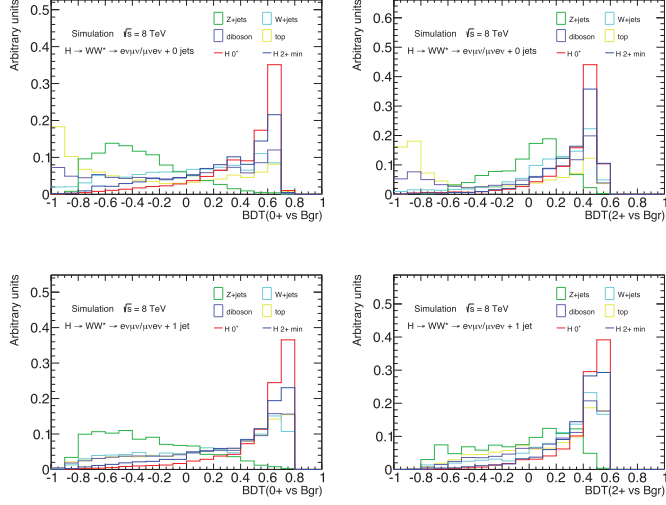


Figure 7.20: Shapes for BDT0 and BDT2 output distributions in the signal region for the spin-2 $\kappa_g = \kappa_q$ with $p_T^H < 300$ GeV benchmark model for the 0-jet (top row) and 1-jet (bottom row) categories.

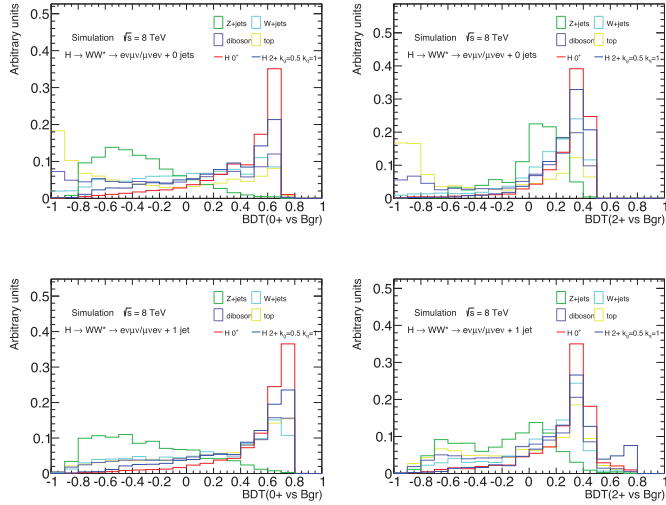


Figure 7.21: Shapes for BDT0 and BDT2 output distributions in the signal region for the spin-2 $\kappa_g = 0.5$, $\kappa_q = 1$ with $p_T^H < 300$ GeV benchmark model for the 0-jet (top row) and 1-jet (bottom row) categories.

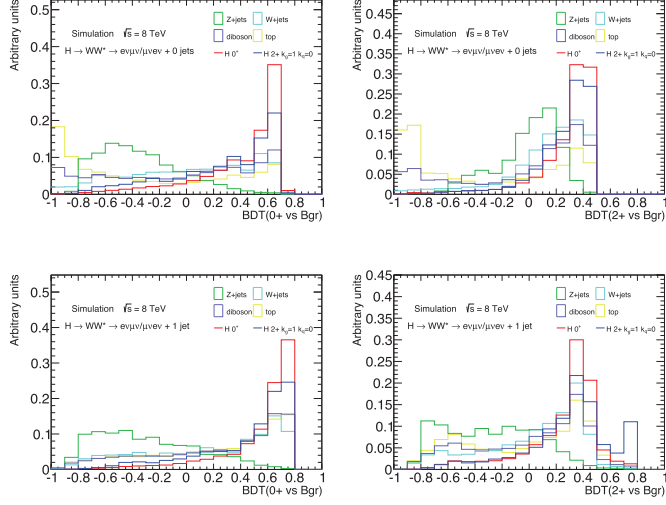


Figure 7.22: Shapes for BDT0 and BDT2 output distributions in the signal region for the spin-2 $\kappa_g = 1$, $\kappa_q = 0$ with $p_T^H < 300$ GeV benchmark model for the 0-jet (top row) and 1-jet (bottom row) categories.

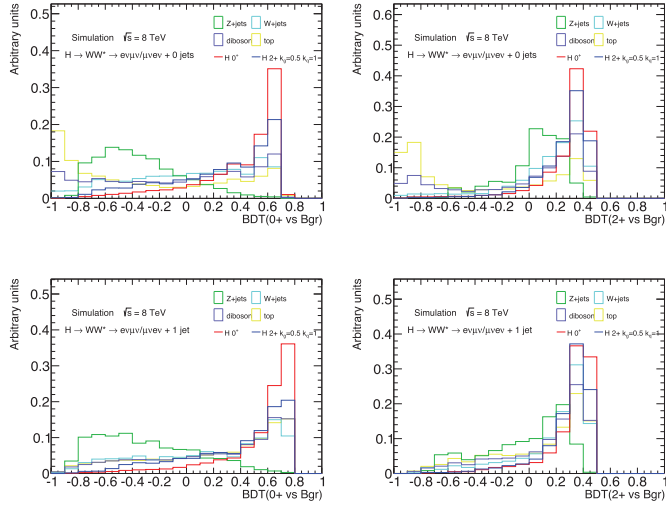


Figure 7.23: Shapes for BDT0 and BDT2 output distributions in the signal region for the spin-2 $\kappa_g = 0.5$, $\kappa_q = 1$ with $p_T^H < 125$ GeV benchmark model for the 0-jet (top row) and 1-jet (bottom row) categories.

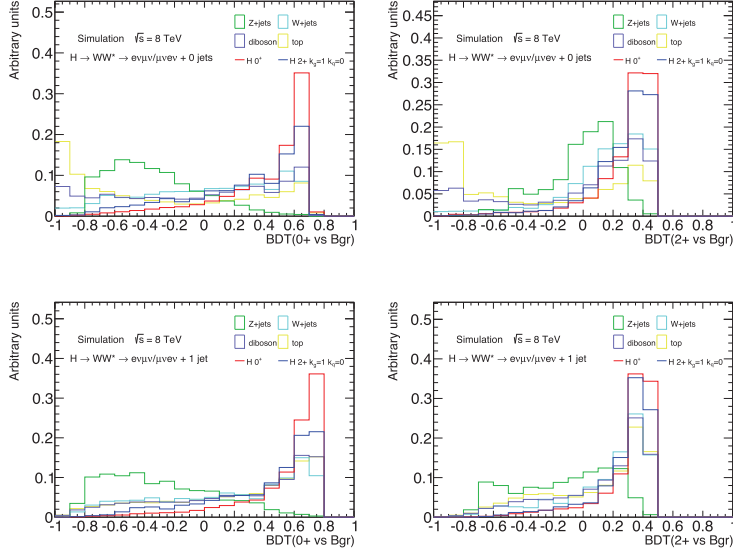


Figure 7.24: Shapes for BDT0 and BDT2 output distributions in the signal region for the spin-2 $\kappa_g = 1$, $\kappa_q = 0$ with $p_T^H < 125$ GeV benchmark model for the 0-jet (top row) and 1-jet (bottom row) categories.

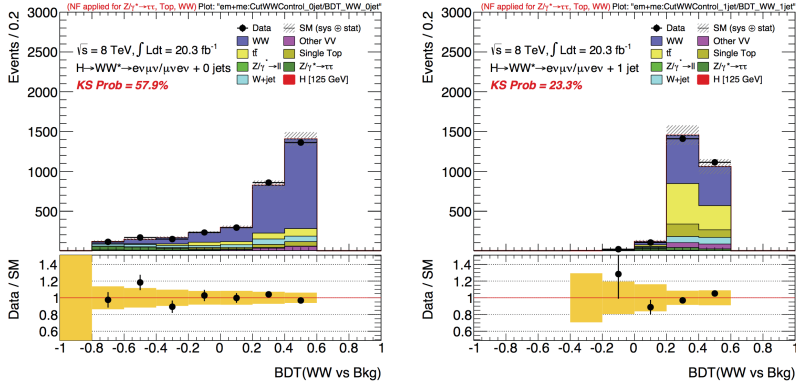


Figure 7.25: BDT output obtained training the WW background as signal against the remaining SM backgrounds. The plots are made in the WW control region, in the 0-jet (left) and 1-jet channels (right), respectively. The normalization factors from control regions are applied. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

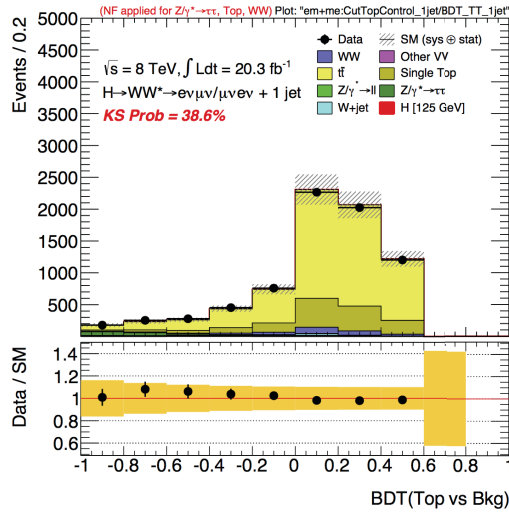


Figure 7.26: BDT output obtained training the top background as signal against the remaining SM backgrounds. The plot is drawn in the top control region. The normalization factors from control regions are applied. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty.

7.1.2 CP Analysis

For the CP analysis only the 0-jet category of the event selection is used. Similar to the spin analysis, two BDT trainings are performed. BDT0 is trained with the SM Higgs sample as signal and all the non-Higgs SM background processes as background. On the other hand, since the spin configurations of the hypotheses are always spin-0 and therefore are more difficult to disentangle, in the CP analysis, a training targeted to distinguish between the two signal hypothesis is required. Thus, the second BDT (called BDT_{CP}) is trained with the SM Higgs signal against the pure alternative BSM CP hypothesis. Therefore, there are two different trainings

- the first aimed to separate the SM Higgs signal against the pure BSM CP-even hypothesis. This analysis is also used to search for a mixed SM and BSM CP-even Higgs;
- the second aimed to separate the SM Higgs signal against the pure BSM CP-odd hypothesis. This analysis is also used to search for a mixed SM and BSM CP-odd Higgs.

No background processes are included in the BDT_{CP} for CP. The trainings are performed twice, as for spin, once in the even-numbered and once in the odd-numbered events. The parameter settings for the BDT_{CP} are shown in Table 7.4.

BDT parameter	Value
BoostType	Gradient
MaxDepth	3
NTrees	400
nEventsMin	5%
UseBaggedGrad	true
GradBaggingFraction	0.5
Shrinkage	0.1

Table 7.4: BDT parameters used in the CP analysis.

The CP analysis is restricted only to the 0-jet bin category. While, as mentioned, BDT0 is exactly the same as for spin, and it has been presented already, BDT_{CP} is different in terms of input variables and settings.

- For BDT_{CP} in the CP-even analysis: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, p_T^{miss} and $p_T^{\ell\ell}$ are used as input variables
- For BDT_{CP} in the CP-odd analysis: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and two additional variables defined as $E_{\ell\nu\nu} = p_T^{\ell 1} - 0.5 \cdot p_T^{\ell 2} + 0.5 \cdot E_T^{\text{miss}}$ (where $p_T^{\ell 1}$ and $p_T^{\ell 2}$ correspond to the transverse momentum of the leading and sub-leading lepton respectively), and $\Delta p_T = |p_T^{\ell 1} - p_T^{\ell 2}|$ are used as input variables

The ranking of the variables is shown in Table 7.5 for the two studies. The $m_{\ell\ell}$ variable is highly ranked since it has the largest discrimination power among the two signal hypotheses tested in both the CP-even and the CP-odd case. In addition, the shapes for the input variables for the CP-even study are shown in Figure 7.27, while for the CP-odd study in Figure 7.28. For both figures, the black solid line corresponds to the non-Higgs background processes and the last bin in each plot includes the overflow.

Ranking	BDT _{CP} CP-even	BDT _{CP} CP-odd
1	$m_{\ell\ell}$	$m_{\ell\ell}$
2	$\Delta\phi_{\ell\ell}$	$E_{\ell\ell\nu\nu}$
3	p_T^{miss}	Δp_T
4	$p_T^{\ell\ell}$	$\Delta\phi_{\ell\ell}$

Table 7.5: Ranking of BDT training variables in the 0-jet final state for the CP-even and CP-odd training.

Before the training, the signal region for the CP analysis is defined similarly to the 0-jet category of the spin analysis. Therefore, the training is performed on the samples after the $p_T^{\ell\ell} > 20$ GeV, as well as the $m_{\ell\ell} > 10$ GeV and $m_{\ell\ell} < 100$ GeV requirements are applied. No p_T^H selection is applied for the CP analysis.

As mentioned, the same BDT analysis is employed for the CP-mixing analyses. The kinematic distributions of a CP-mixed state signal are intermediate between the two pure CP-states. The training procedure is not repeated for each mixed state, but the training weights from the trainings on pure states are applied for the classification of the mixed ones.

7.1.2.1 Overtraining Check

Similar to the spin analysis, the Kolmogorov-Smirnov test is employed to test the impact of statistical fluctuations on the BDT discriminant. For each CP hypothesis the training and testing BDT output distribution are compared. For BDT0 and BDT_{CP} the KS probabilities are 27.5% (41.6%) and 100% (14.9%) for signal and background respectively for the CP-even (CP-odd) analysis.

7.1.2.2 Modelling of the Input Variables

To check the modelling of the input variables their distributions are plotted in the control regions of the analysis and the agreement of the data to the background estimation is tested. Figures 7.29 and 7.30 shows the distributions for the additional variables that are used in the CP analysis in the WW and $Z/\gamma^* \rightarrow \tau\tau$ control regions of the 0-jet category. The data agree with

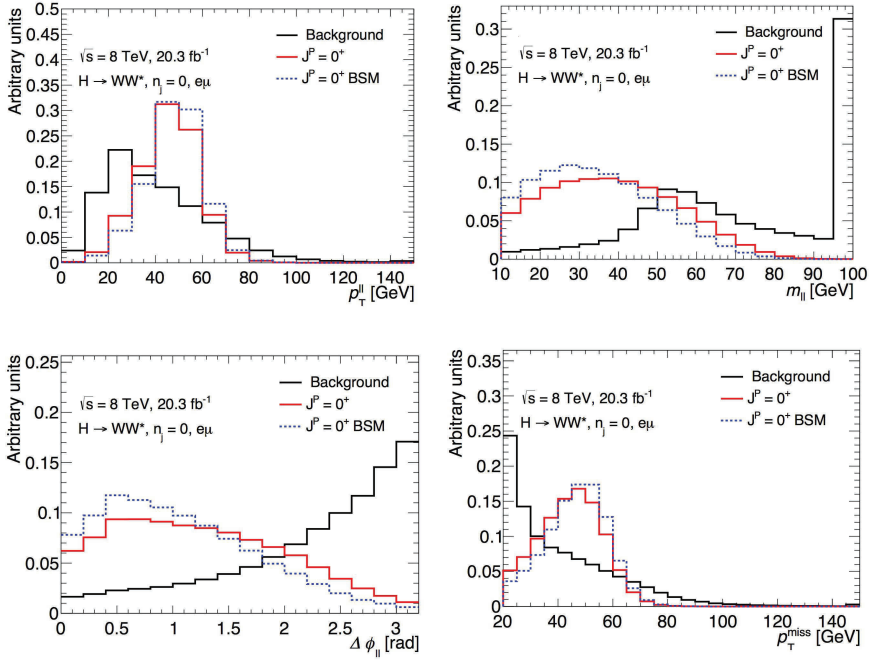


Figure 7.27: $p_T^{\ell\ell}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and p_T^{miss} distributions for the SM Higgs signal (solid red line) and the BSM CP-even Higgs signal (dashed blue line) after the no-jet requirement. The expected shapes for the sum of all backgrounds, including the data-derived $W + \text{jets}$ background is shown (solid black line). The last bin in each plot includes the overflow.

the Monte Carlo simulation well within the statistical and systematic uncertainty. Therefore, no mis-modelling of the input variables of the CP analysis is observed.

7.1.2.3 Correlations of Input Variables

Figures 7.31 and 7.32 (7.33 and 7.34) show the scatter plots among pairs of training variables used in the BDT_{CP} for the SM signal versus the BSM CP-even (CP-odd) signal. The BDT_0 correlations are the same as for the aforementioned ones used in spin analysis. Large correlations are observed between the $\Delta\phi_{\ell\ell}$ and $m_{\ell\ell}$ distributions, as well as between the $E_{\ell\ell\nu\nu}$ and Δp_T , as expected.

Table 7.6 shows the mean values of the linear correlation coefficient, calculated among pairs of the input variables for BDT_{CP} . Apart from the linear correlations, Figures 7.35 and 7.36 show the profile plots of the pairs of variables in the WW and in the $Z/\gamma^* \rightarrow \tau\tau$ control region respectively. A very

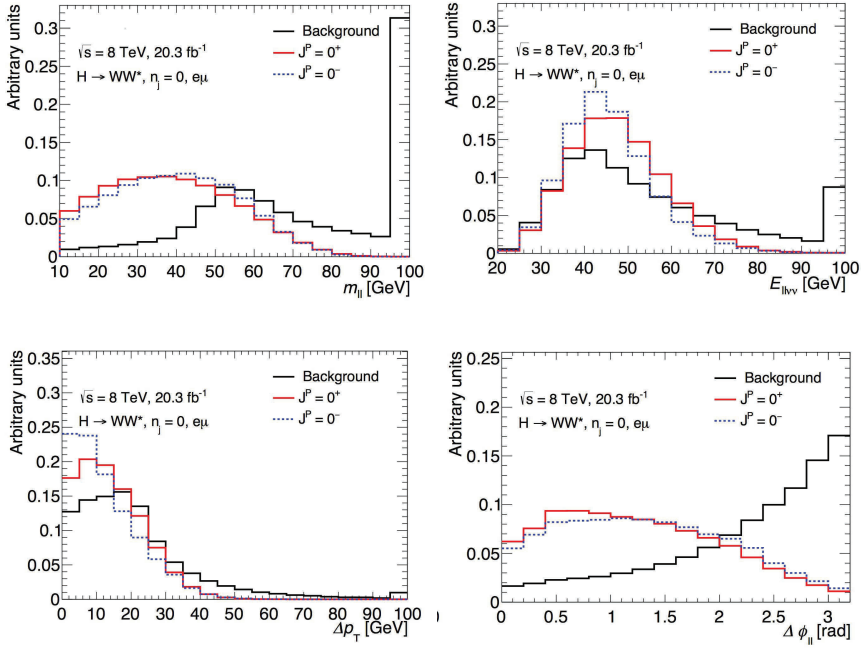


Figure 7.28: $m_{\ell\ell}$, $E_{\ell\ell\nu\nu}$, Δp_T and $\Delta\phi_{\ell\ell}$ distributions for the SM Higgs signal (solid red line) and the BSM CP-odd Higgs signal (dashed blue line) after the no-jet requirement. The expected shapes for the sum of all backgrounds, including the data-derived $W + \text{jets}$ background is shown (solid black line). The last bin in each plot includes the overflow.

good agreement among data and Monte Carlo expectation, within statistical uncertainties, is observed.

CP-even	$E_{T\text{miss}} m_{\ell\ell}$	$p_T^{\text{miss}} \Delta\phi_{\ell\ell}$	$p_T^{\text{miss}} p_T^{\ell\ell}$	$\Delta\phi_{\ell\ell} m_{\ell\ell}$	$m_{\ell\ell} p_T^{\ell\ell}$	$\Delta\phi_{\ell\ell} p_T^{\ell\ell}$
WW : data	0.09 ± 0.02	-0.47 ± 0.01	0.93 ± 0.00	0.17 ± 0.02	0.09 ± 0.02	-0.50 ± 0.01
WW : bkg	0.09 ± 0.00	-0.48 ± 0.00	0.92 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	-0.50 ± 0.00
$Z\tau\tau$: data	0.21 ± 0.02	-0.06 ± 0.02	0.57 ± 0.01	0.22 ± 0.02	0.35 ± 0.02	-0.10 ± 0.02
$Z\tau\tau$: bkg	0.23 ± 0.00	-0.04 ± 0.01	0.53 ± 0.00	0.23 ± 0.00	0.35 ± 0.00	-0.07 ± 0.00
CP-odd	$m_{\ell\ell} E_{\ell\ell\nu\nu}$	$m_{\ell\ell} \Delta p_T$	$\Delta\phi_{\ell\ell} E_{\ell\ell\nu\nu}$	$\Delta\phi_{\ell\ell} \Delta p_T$	$E_{\ell\ell\nu\nu} \Delta p_T$	$m_{\ell\ell} \Delta\phi_{\ell\ell}$
WW : data	0.19 ± 0.02	0.11 ± 0.02	-0.04 ± 0.02	0.14 ± 0.02	0.92 ± 0.00	0.12 ± 0.02
WW : bkg	0.19 ± 0.00	0.08 ± 0.00	-0.01 ± 0.00	0.18 ± 0.00	0.91 ± 0.00	0.10 ± 0.00
$Z\tau\tau$: data	0.47 ± 0.02	0.32 ± 0.02	-0.04 ± 0.02	-0.01 ± 0.02	0.95 ± 0.00	0.22 ± 0.02
$Z\tau\tau$: bkg	0.47 ± 0.00	0.32 ± 0.00	-0.01 ± 0.01	0.01 ± 0.01	0.95 ± 0.00	0.22 ± 0.00

Table 7.6: Mean values of the correlation distributions in the WW and $Z\tau\tau$ control regions, for the CP-even and CP-odd analyses, respectively.

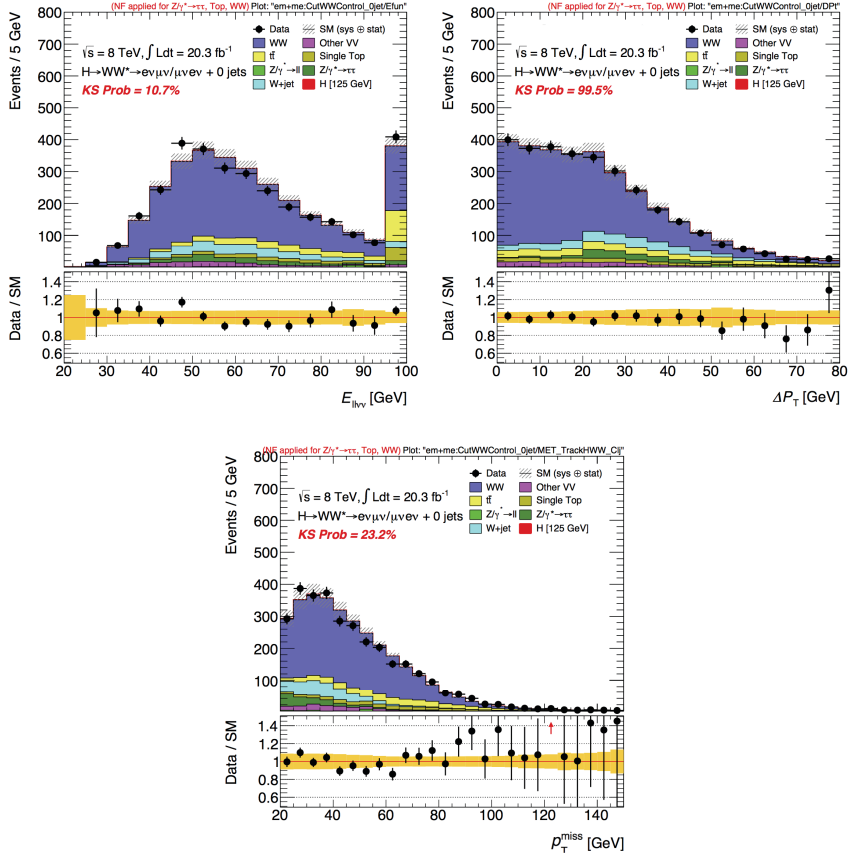


Figure 7.29: The distributions for the input variables of the CP analysis in the WW control region of the 0-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

7.1.2.4 Modelling of the BDT_{CP} Discriminant

Figure 7.37 shows the BDT_{CP} distributions for the CP-even and the CP-odd study in the the WW and $Z/\gamma^* \rightarrow \tau\tau$ control regions. In addition, the shapes of the BDT_{CP} output distributions for the SM and the alternative hypotheses, as well as for the major background processes are shown in the bottom row of the same figure.

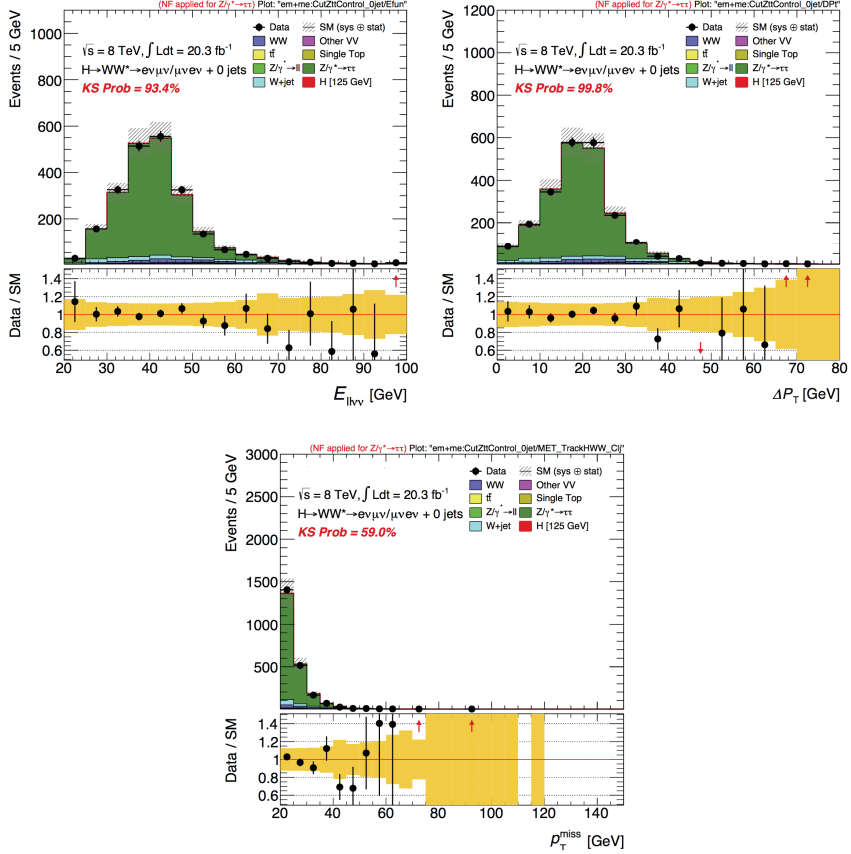


Figure 7.30: The distributions for the input variables of the CP analysis in the $Z/\gamma^* \rightarrow \tau\tau$ control region of the 0-jet category. Below each plot, the ratio of the data to the background expectation is plotted. The orange band shows statistical and systematic uncertainty.

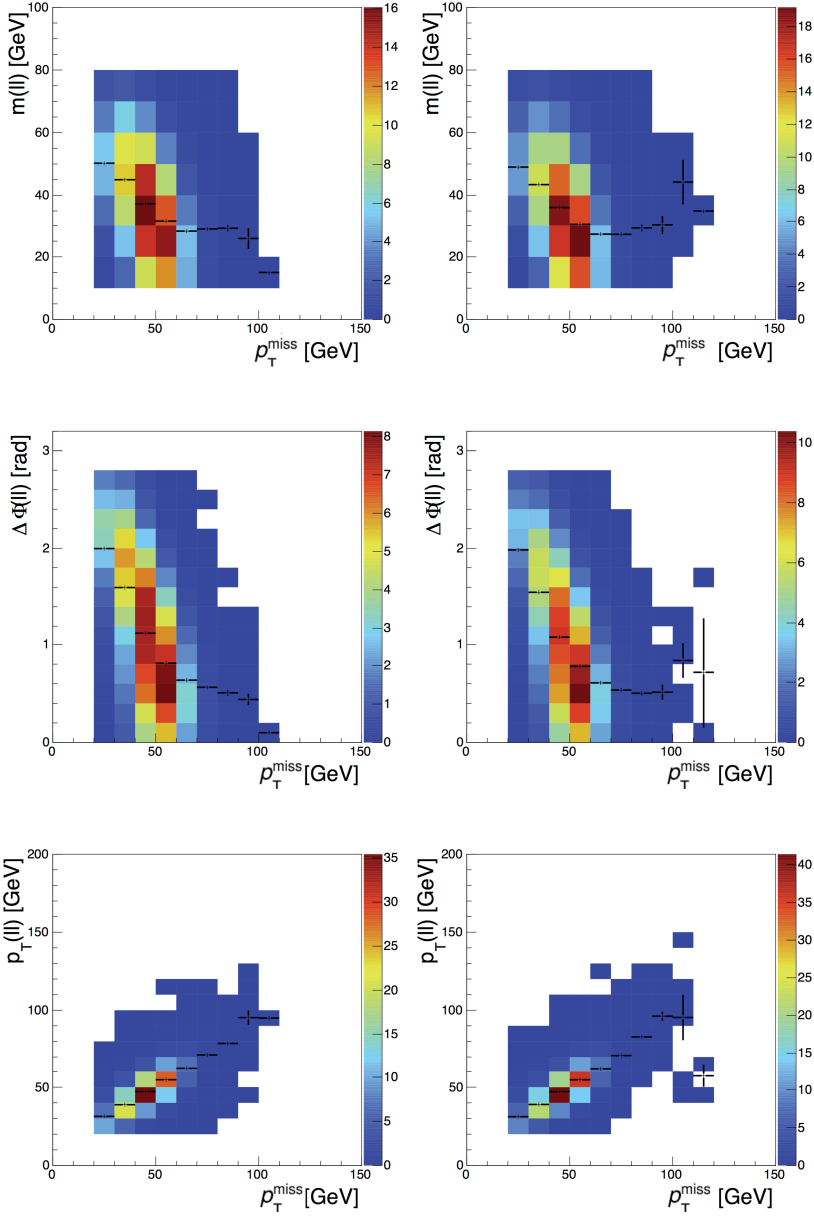


Figure 7.31: Scatter plots for pairs of BDT_{CP} input variables for the SM CP-even signal (left) and the BSM CP-even signal (right).

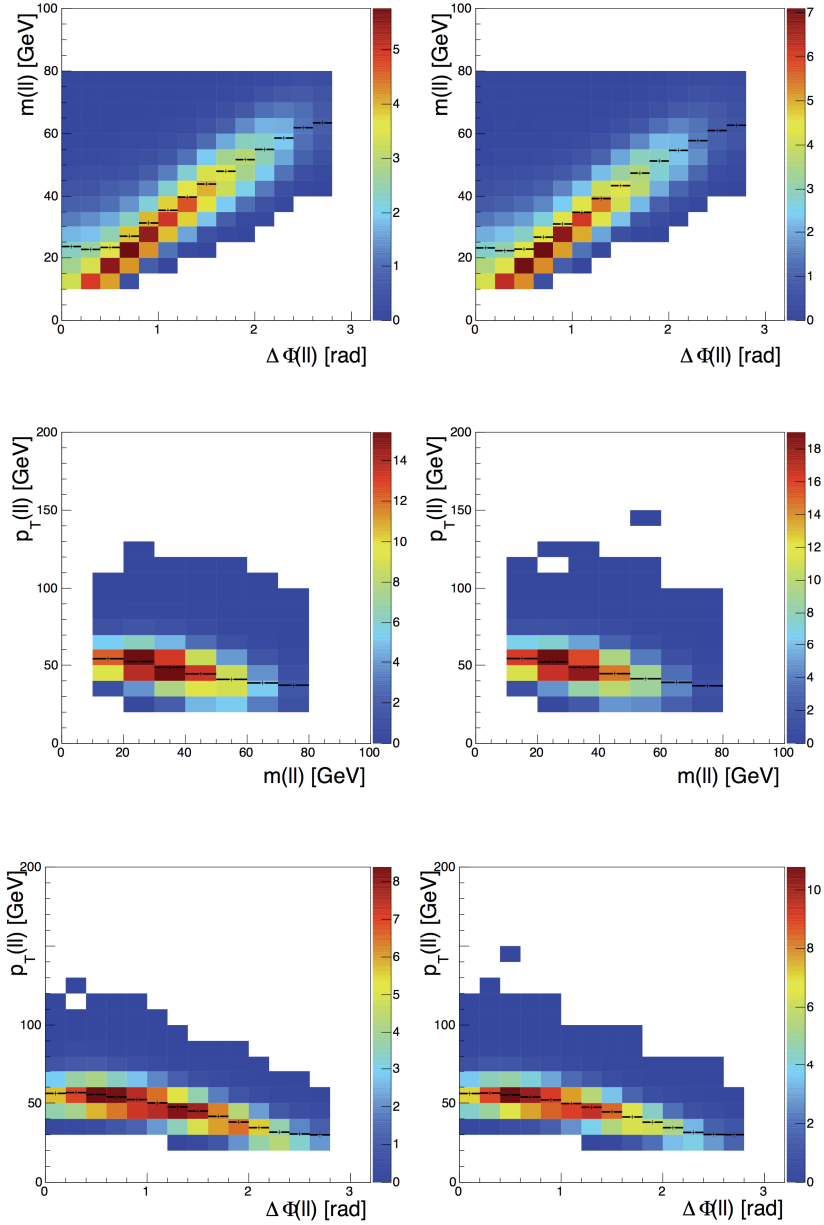


Figure 7.32: Scatter plots for pairs of BDT_{CP} input variables for the SM CP-even signal (left) and the BSM CP-even signal (right).

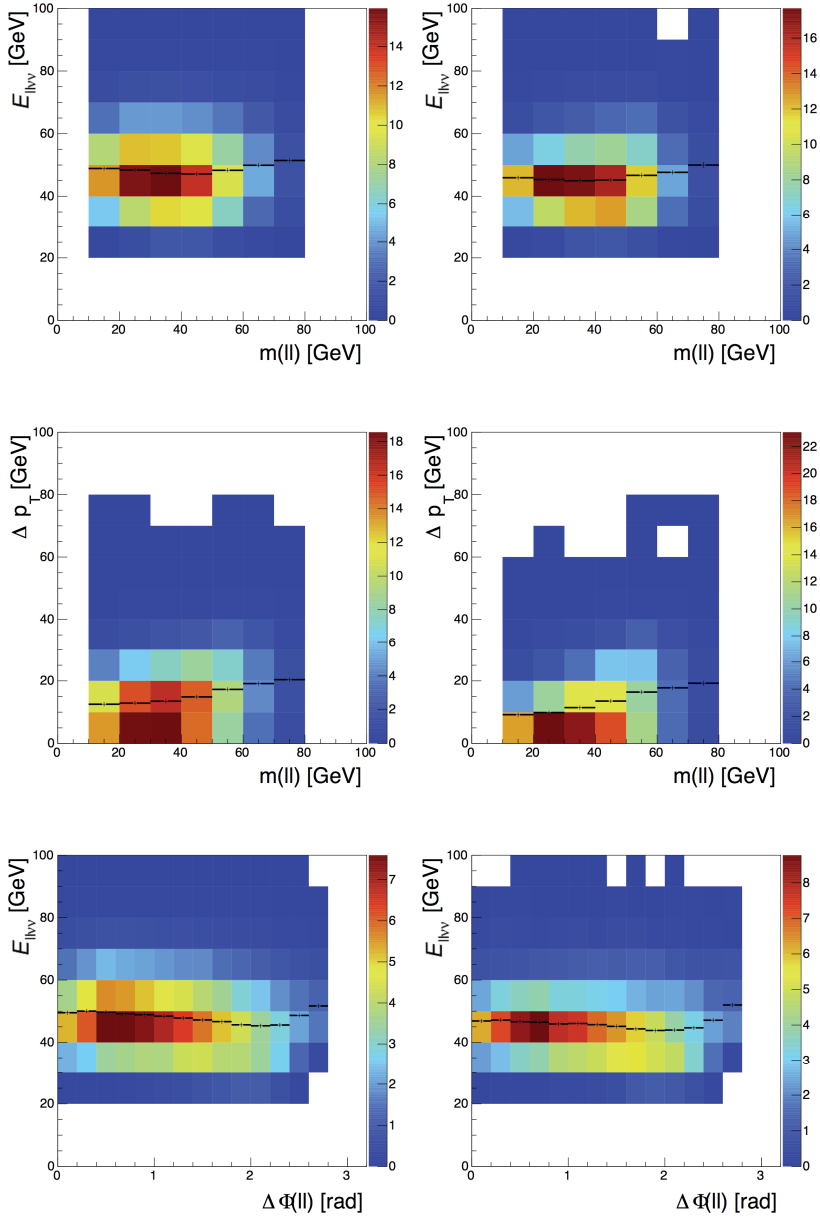


Figure 7.33: Scatter plots for pairs of BDT_{CP} input variables for the SM CP-even signal (left) and the BSM CP-odd signal (right).

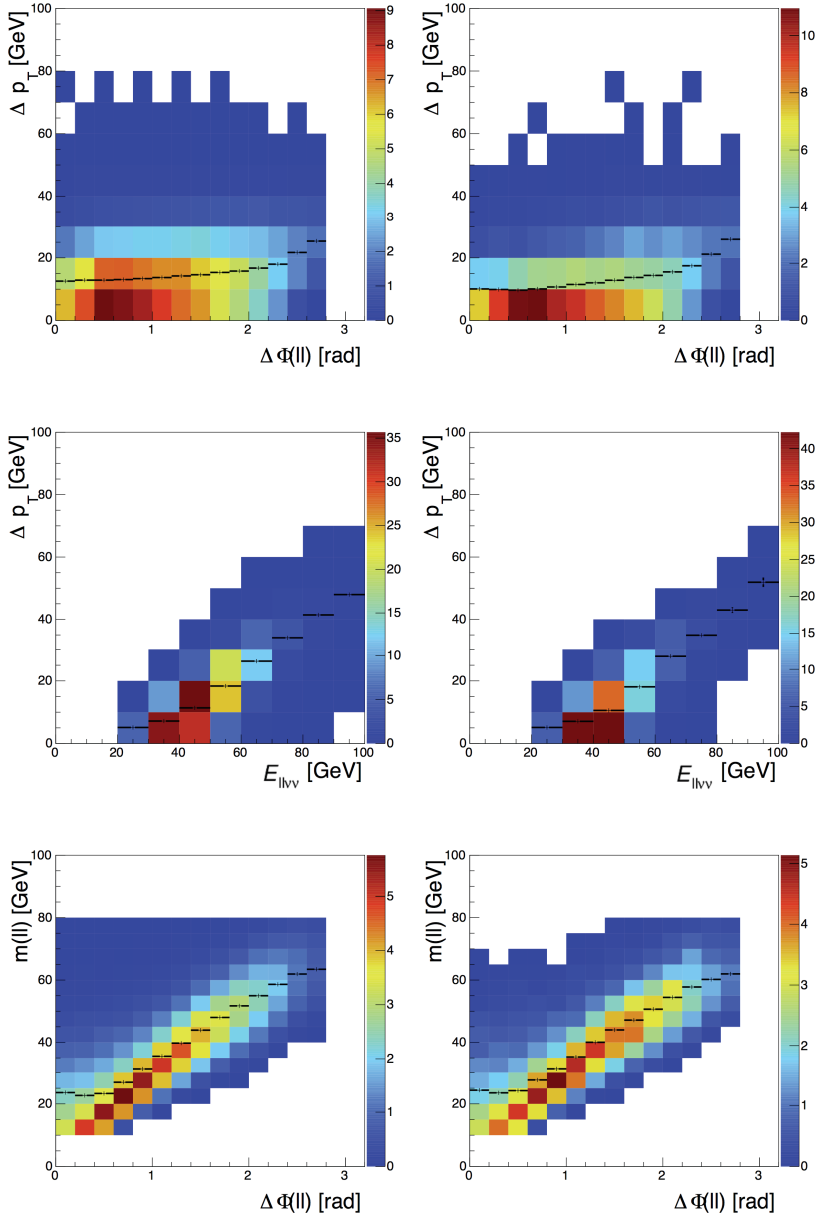


Figure 7.34: Scatter plots for pairs of BDT_{CP} input variables for the SM CP-even signal (left) and the BSM CP-odd signal (right).

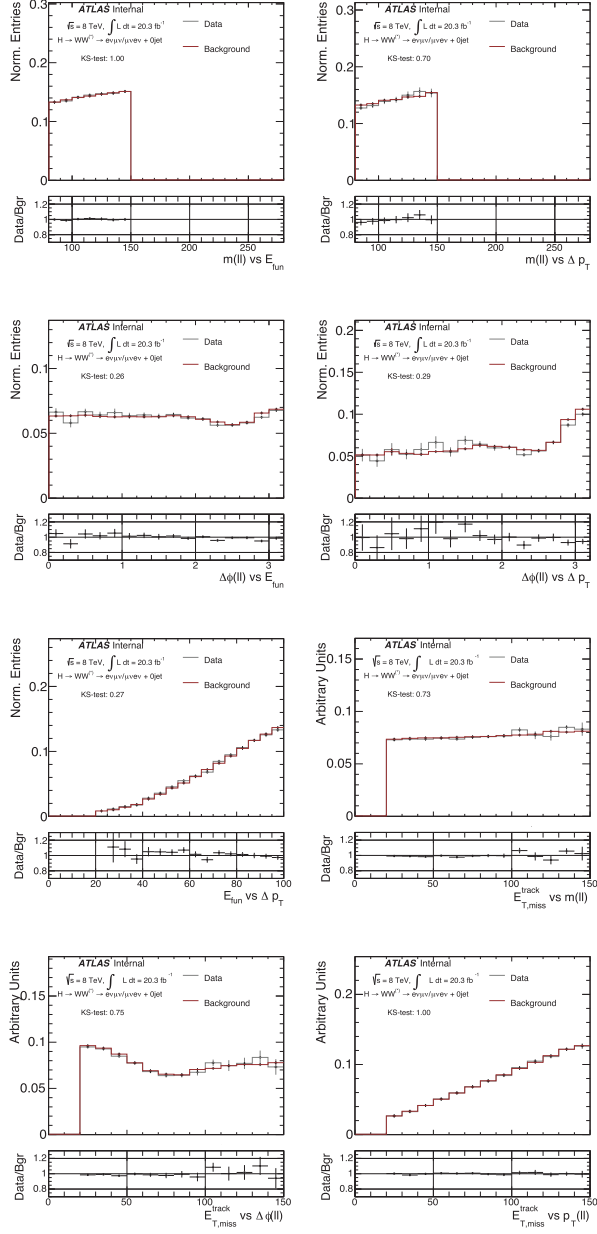


Figure 7.35: Profile scatter plots in the WW control region with 0 jets for pairs of BDT_{CP} input variables for data and backgrounds superimposed for the CP-even and CP-odd BSM analyses. The ratio below each plot shows the agreement of the data to the background expectation. Error bars include statistical uncertainty.

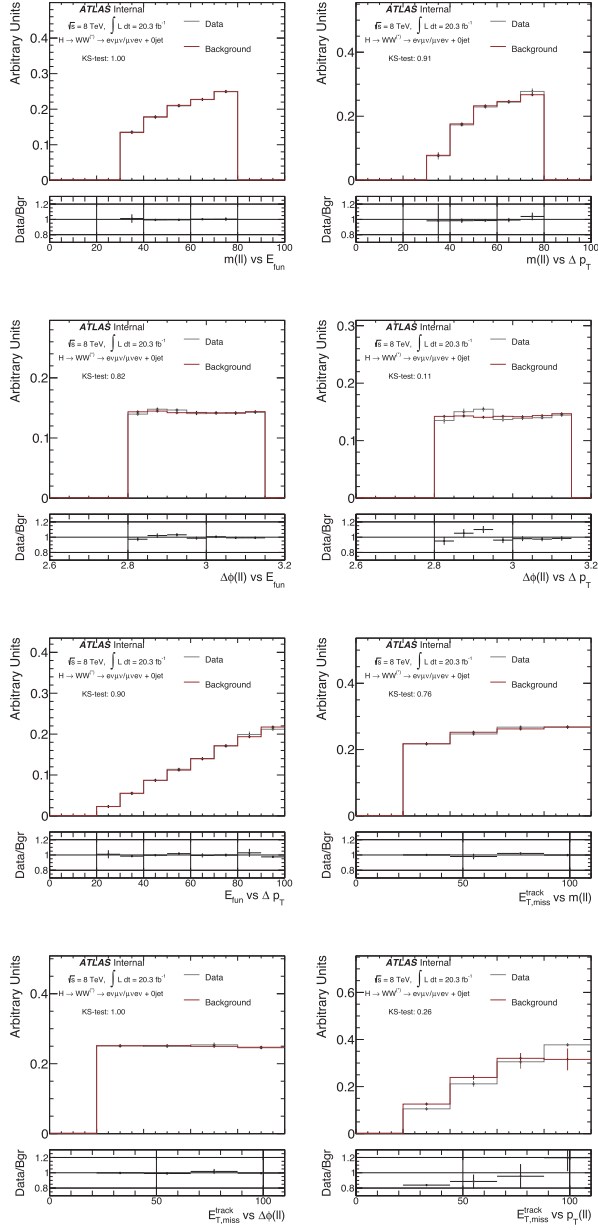


Figure 7.36: Profile scatter plots in the $Z/\gamma^* \rightarrow \tau\tau$ control region with 0 jets for pairs of BDT_{CP} input variables for data and backgrounds superimposed for the CP-even and CP-odd BSM analyses. The ratio below each plot shows the agreement of the data to the background expectation. Error bars include statistical uncertainty.

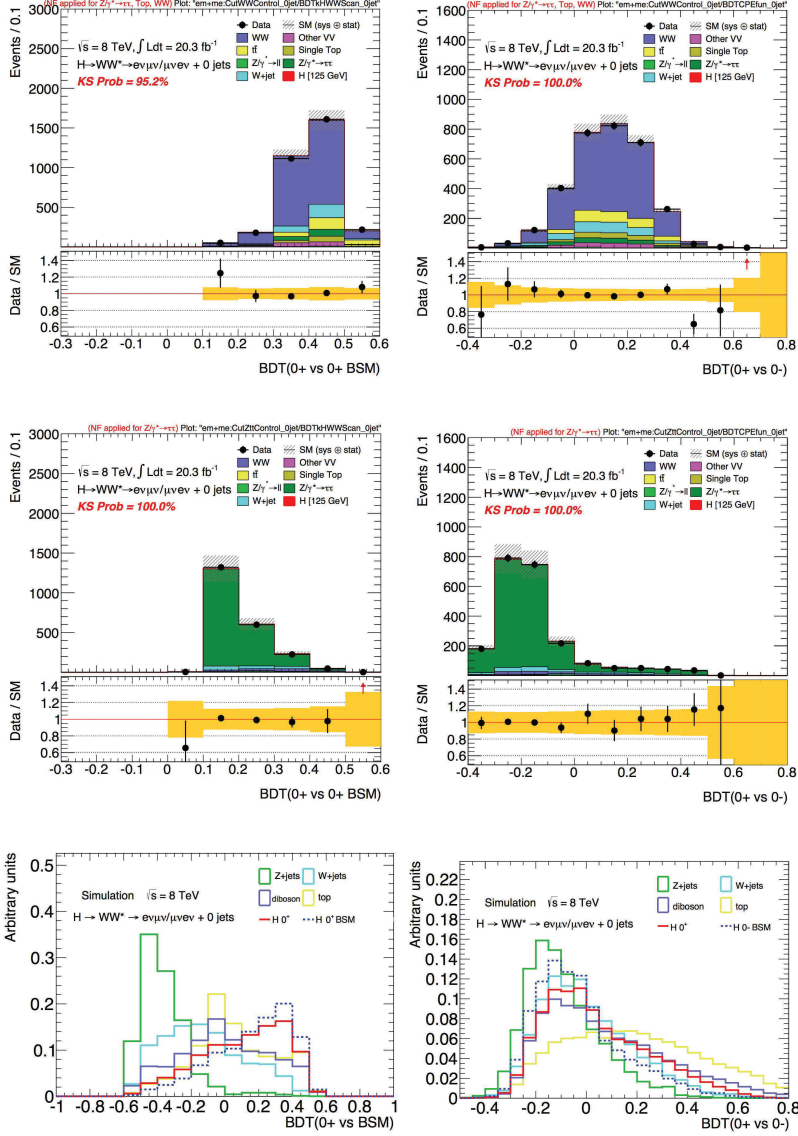


Figure 7.37: BDT_{CP} output distributions for the CP-even (left) and CP-odd (right) study in the WW (top row) and the Z/γ* → ττ (middle row) control region. The ratio below each plot tests the compatibility of the data to the background expectation. The orange band includes statistical and systematic uncertainty. Finally, the bottom row shows the shapes of the distribution for the signals and the background processes in the signal region.

7.2 Statistical Treatment

In this section, the statistical treatment of the analysis will be discussed. As discussed already, in the 2014 analysis there are two types of statistical tests: the fixed hypothesis test for the spin analysis, as well as the analysis designed to distinguish between the SM CP-hypothesis and the alternative BSM CP-states. In addition, for the CP-mixing analysis, a different procedure is applied for the scans of the EFT parameters. For these tests, the two-dimensional BDT0×BDT2 space is unrolled row-by-row into one-dimensional distribution on which the fit is performed. In the 2014 analysis an optimisation on the binning of this unrolled distribution was studied and is presented in this section.

7.2.1 Procedure for the Spin Analysis

The statistical treatment of the spin analysis in the 2014 study is the same as one used for the 2013 analysis, which is discussed in detail in Section 6.6. The statistical analysis of the data employs the same binned likelihood $\mathcal{L}(\varepsilon, \theta)$, constructed with one parameter of interest, ε . The overall signal normalisation, $\mu > 0$, is taken as nuisance parameter. Due to the lack of a cross-section estimate for a spin-2 particle under the assumptions of the benchmark models that are tested, the event yields of the alternative signal hypotheses in the signal region are normalised to the same number as for the SM signal hypothesis.

In addition, the same definitions for the test statistics and the CL_S estimator are used, as for the 2013 analysis, while pseudo-experiments are performed in order to obtain the test statistics distribution.

7.2.2 Procedure for CP Analysis

The definition of the likelihood for the CP analysis is the same as for spin. The parameter of interest ε corresponds to the SM signal hypothesis when $\varepsilon = 1$ and to the alternative parity hypothesis (pure BSM CP-even, pure BSM CP-odd Higgs or the CP-mixed state) when $\varepsilon = 0$.

When testing the SM hypothesis against the pure BSM CP-even and pure BSM CP-odd signal hypothesis, the same procedure as for the spin analysis is followed. The test statistics distribution q remains the same as for spin, the final result for the fixed hypothesis test is estimated by running pseudo-experiments and is expressed in terms of the CL_S estimator.

On the other hand, for the CP-mixing analysis, the method employed is the asymptotic approximation [155], which is valid due to the increased statistics. For the asymptotic approximation approach, fits are performed to the data and to the Monte Carlo expectation under the SM (BSM) hypothesis and no pseudo-experiments are performed. Each of these fits corresponds to one value of the scanning parameter. Then, two fits to the SM expectation are evaluated: fixing the normalisation of the signal to the SM expected one, and to the observed SM signal normalisation. Extracted from the fit is the value

of the log-likelihood (LL) and is given as a function of the scan parameter (i.e. CP-mixing fraction). The maximum of the LL values is determined and then the difference from all the other values is computed, $-2\Delta LL$. The final result is the $-2\Delta LL$ as a function of the scanning parameter, when normalised to the maximum LL value. Finally, for this formalism, the 1σ and 2σ lines are found at $-2\Delta LL = 1$ and $-2\Delta LL = 3.84$, respectively.

7.2.3 Binning

The fits for the final results are performed on the one-dimensional distribution which is the result of the row-by-row unrolling of the BDT0×BDT2 (or BDT0×BDT_{CP}) space. In order to avoid empty bins in the unrolled BDT output distribution, a basic bin merging algorithm is applied. The purpose of this algorithm is not to improve the sensitivity. In addition, the merging scheme, or the so-called *binning configuration* is created once for the nominal distribution and is then applied on all systematic variations.

Independent binning configurations are created for the different jet-bins of the spin analysis, as well as for the various benchmark models for the spin and CP analyses. The merging of bins is based only on the threshold on the minimum number of background events that are required in each bin, and is therefore independent of the signal events. A different binning configuration is adopted for each different BDT training.

The algorithm for the merging works as follows; if a bin contains less than 1 background event is marked as "empty" and it is then merged with a neighbouring bin. This one event is applied on the sum of weighted background events, so after the normalisation to the corresponding cross section and luminosity has taken place. In the two-dimensional space, an "empty" bin is merged with the left neighbouring bin in the same BDT0 row. If this bin is also empty then the procedure is repeated until a non-empty bin is found. If the empty bin happens to be the first left bin in the row, then it is merged within the same BDT0 with the right neighbouring.

The initial binning, before the merging has occurred is the following:

- Spin-2 $\kappa_g = \kappa_q$:
 - 0-jet : 10x5 bins
 - 1-jet : 5x5 bins
- Spin-2 $\kappa_g = 0.5$ and $\kappa_q = 1$ (for both $p_T^H < 125$ GeV and $p_T^H < 300$ GeV):
 - 0-jet : 10x5 bins
 - 1-jet : 5x5 bins
- Spin-2 $\kappa_g = 1$ and $\kappa_q = 0$ (for both $p_T^H < 125$ GeV and $p_T^H < 300$ GeV):
 - 0-jet : 10x5 bins

- 1-jet : 5x5 bins
- Spin-0⁺ SM versus spin-0⁺ BSM:
 - 0-jet : 5x15 bins
- Spin-0⁺ SM versus spin-0⁻ BSM:
 - 0-jet : 5x15 bins

The increased number of bins for the second BDT, the BDT_{CP} , for the CP analysis is driven by the need of a finer binning to exploit the shape differences between the different CP scenarios in the scheme or relatively low sensitivity.

7.3 Impact of Systematic Uncertainties

The systematic uncertainties are treated as nuisance parameters in the likelihood definition for the fit. The two categories of systematic uncertainties, the detector systematic and the modelling ones, will be discussed in the following.

7.3.1 Detector Systematics

The sources of the detector systematics are closely linked to the physics objects definition and how well the ATLAS detector can reconstruct and identify them. Table 7.7 summarises the sources of the experimental systematic uncertainties. Dedicated Monte Carlo simulated samples with systematically varied parameters were analysed to determine the uncertainties incorporated in the fit. Most of the detector systematic uncertainties have negligible impact on the final results. The dominant sources of uncertainty are summarised in Table 7.8 along with their impact on the signal and background event yields in the signal region.

7.3.2 Modelling Uncertainties

Special attention is required for the dominant background processes of the non-resonant WW , Top and $Z/\gamma^* \rightarrow \tau\tau$. The uncertainties related on the normalisation of this backgrounds have already been discussed in Chapter 5. In addition, the modelling uncertainties that affect the shape of these backgrounds are addressed. Finally, the uncertainty on the modelling of the SM Higgs signal is also important and is discussed in the following.

7.3.2.1 WW Modelling

As far as the normalisation uncertainty of the WW background process is concerned, this is split into four components as has been already discussed. The scale uncertainty on the Monte Carlo predictions for the BDT discriminant

Source of Uncertainty	Treatment in the analysis and the size
Jet Energy Resolution (JER)	below 5% as a function of jet η and p_T
Jet Energy Scale (JES)	below 7% in total as a function of jet η and p_T 12 sources of uncertainties are considered: – in-situ: Detector 1, Modeling 1 – η intercalibration: modeling, stats+method – high p_T jets – pile-up: in-time pile-up, out-of-time pile-up, p_T , ρ topology – flavor composition and flavor response – b -JES
Electron Selection Efficiency	reconstruction: 0.1 - 1% depending on E_T and η identification: 0.2 - 2.7% depending on E_T and η
Electron Energy Scale	about 0.4% depending on E_T and η except for crack region
Electron Energy Resolution	about 1% depending on E_T and η
Muon Selection Efficiency	below 0.5% depending on p_T and η
Muon Momentum Scale	below 0.5% depending on p_T and η
Muon Momentum Resolution	below 1% depending on p_T and η
Missing Transverse Energy	lepton and hard jet energy uncertainties are propagated to $E_T^{\text{miss,J-TRK}}$ resolution and scale variation of soft terms
Pile-up	variation of the μ rescaling to 0.8 and 1.0 with nominal value of 0.9
b -tagging systematics	b -tagging and light or c -jets misidentification uncertainties using 1σ method
Luminosity	2.8% [150]

Table 7.7: Sources of systematic uncertainty per object or event

is studied by varying the factorisation and renormalisation scales by a factor of 0.5 and 2.0. The parton shower uncertainty is evaluated by comparing the HERWIG and PYTHIA parton shower programs. The PDF uncertainty is evaluated by combining the CT10 PDF error set with the difference among the central values of NNPDF and CT10. Finally, the uncertainty on the choice of the generator used for the modelling is evaluated by comparing the MC@NLO and POWHEG generators. The summary of the pre-fit normalisation uncertainties is shown in Table 7.9. These are determined independently on the final (unrolled and rebinned) BDT output distribution for each benchmark of the spin and CP analysis.

The same uncertainties that affect the normalisation have been tested to verify if they also affect the shape of the WW background in the unrolled BDT discriminant. If the shape variation is larger than $\approx 5\%$ then the uncertainty is also considered as shape uncertainty. The scale and PDF uncertainties have been found to have negligible impact on the shape. However, this is not the case for the parton shower and generator modelling uncertainties. Two envelopes are created around the nominal WW unrolled BDT distribution: one for the parton shower and one for the generator modelling uncertainty. These are created by varying bin-by-bin the distribution of the WW . Furthermore, since each BDT training has its own binning configuration, the WW envelopes are created for each benchmark model. Figures 7.38 and 7.39 show the envelopes

Source of Uncertainty 0 jet	SM Higgs	WW + top	Z/γ^* +jets	W +jets	total Bkg
Jet Energy	14	4.1	7.4	–	3.9
W +jets Fake Factor	–	–	–	26	2.4
Electron systs	7.8	1.1	2.1	–	1.2
Muon systs	6.3	0.3	0.4	–	0.3
$E_T^{\text{miss},J-\text{TRK}}$ syst	6.2	0.1	12.1	–	2.7
MC Statistics	1.2	0.3	1.9	1.6	0.5

Source of Uncertainty 1-jet SR	SM Higgs	WW + top	Z/γ^* +jets	W +jets	total Bkg
Jet Energy	6.8	2.1	10	–	3.2
W +jets Fake Factor	–	–	–	25	2.5
Electron systs	2.3	1.5	1.9	–	1.3
Muon systs	1.8	0.3	0.8	–	0.6
$E_T^{\text{miss},J-\text{TRK}}$ syst	1.7	0.1	9.1	–	2.5
b -tag	3.0	1.9	–	2.0	–
MC Statistics	1.9	0.6	2.7	3.3	0.9

Table 7.8: Largest detector systematic uncertainties in % on signal (SM Higgs), WW +top, Z +jets, W +jets backgrounds and the total background in the signal region.

generated for different spin and CP benchmarks respectively for the parton shower uncertainty. Similarly, Figures 7.40 and 7.41 shows the envelopes for the uncertainty on the choice of the generator. A final uncertainty that is considered in the continuous WW background process, is the uncertainty due to higher-order electroweak corrections. These are corrections that are applied to the diboson production and result in a $\approx 4\%$ difference on the inclusive cross sections, and they are in agreement with the observations in data. The uncertainty is determined by a re-weighting procedure of the simulated MC sample towards the NLO electroweak calculation [156], where the difference with respect to the nominal is estimated.

7.3.2.2 Top Modelling

The top background process becomes crucial when including the 1-jet category. The uncertainties that are linked to the normalisation of the top background are similar to the WW case. The scale uncertainty is estimated by varying the renormalisation and factorisation scales by factors of 0.5 and 2.0. The same PDF sets as for the WW are used for the PDF uncertainty, while the parton showering modelling is also evaluated by comparing HERWIG and PYTHIA. Finally, for the generator uncertainty, the uncertainty is taken by comparing the MC@NLO and ALPGEN generators.

The same uncertainties are tested to verify if they affect the shape of the one-dimensional unrolled BDT distribution of the 1-jet category. As far as the scale uncertainty and the PDF uncertainty are concerned, they are found to be negligible, and they are not considered in the fit. On the other hand the parton shower uncertainty and the choice of the generator are found to have

a maximum deviation of $\approx 6\%$ and they are added as nuisance parameters in the final fit.

Table 7.9 summarises the pre-fit normalisation uncertainties considered for the top background process.

7.3.2.3 $Z/\gamma^* \rightarrow \tau\tau$ Modelling

For the Z/γ^* the scale uncertainties are also evaluated by varying the normalisation and factorisation scale by 0.5 and 2.0. In addition, for the PDF set uncertainty, the nominal sample was generated using the CTEQ6 PDF set. The simulated events are re-weighted towards CT10, MSTW2008 and NNPDF2.3. The total uncertainty is taken as a quadrature sum of the CT10 uncertainty and the maximum difference between CT10 and the other PDF sets. Furthermore, as far as the generator modelling uncertainty is concerned, a comparison between ALPGEN+PYTHIA6 and SHERPA is performed at reconstruction level.

Finally, a mis-modelling of the p_T^Z , which is reconstructed at $p_T^{\ell\ell}$ was observed in the control region of the Drell Yan process, especially for the 0-jet category, as discussed in Chapter 5. This is due to the fact that the ALPGEN+HERWIG generator cannot model adequately the parton shower of the soft jets that balance the $p_T^{\ell\ell}$ distribution when there are no reconstructed jets in the final state. The correction for this mis-modelling is evaluated by comparing the data to the Monte Carlo estimation in the Z peak. From this comparison, weights are extracted which are then applied to the Monte Carlo events in the 0-jet bin category. A systematic uncertainty is considered for this re-weighting. Except for the nominal weights for the re-weighting an additional set of weights for events with $p_T^{\text{miss}} > 20$ GeV around the Z mass peak are extracted. The uncertainty on the p_T^Z re-weighting is estimated by comparing the effects of the re-weighting when using these two different sets of weights.

Table 7.9 summarises the uncertainties considered for the Z/γ^* background process. No shape uncertainties are considered for this process.

7.3.2.4 Higgs Modelling

The observables that are used for the BDT analysis are affected by the underlying p_T^H distribution. However, as it has been mentioned already, the spectrum of the SM Higgs transverse momentum is re-weighted to the NLO POWHEG+PYTHIA generator prediction. No additional shape uncertainty is considered, since the theory prediction is already at NNLO+NNLO.

The normalisation in terms of event yields is increased by 10% in the 0-jet category and decreased by 15% in the 1-jet category. The shapes of the variables are found to have deviations, mainly in the tails, for up to 20% in the 0-jet and 10 – 20% in the 1-jet category.

However, for the spin-2 models, no theoretical uncertainties are considered. These uncertainties are negligible when compared to the large approximations

Category	Scale	PDF	Gen	EW	UE/PS	p_T^Z	Total
WW Background							
SR 0-jet	0.9	3.8	6.9	-0.8	-4.1	-	8.9
SR 1-jet	1.2	1.9	3.3	-2.1	-3.2	-	5.5
Top-quark Background							
SR 1-jet	-0.8	-1.4	1.9	-	2.4	-	3.5
$Z\gamma^* \rightarrow \tau\tau$ Background							
SR 0-jet	-7.1	1.3	-	-	-6.5	19	21.3
SR 1-jet	6.6	0.66	-	-	-4.2	-	7.9

Table 7.9: Pre-fit modelling uncertainties on the extrapolation factor for the WW , top-quark and Z/γ^* backgrounds. The last column refers to the sum in quadrature of all uncertainties. The negative sign indicates anti-correlation with respect to the uncertainties that have no sign and are in the same column.

and uncertainties that are present in the models, as for example the p_T^H selection in the models with non-universal couplings.

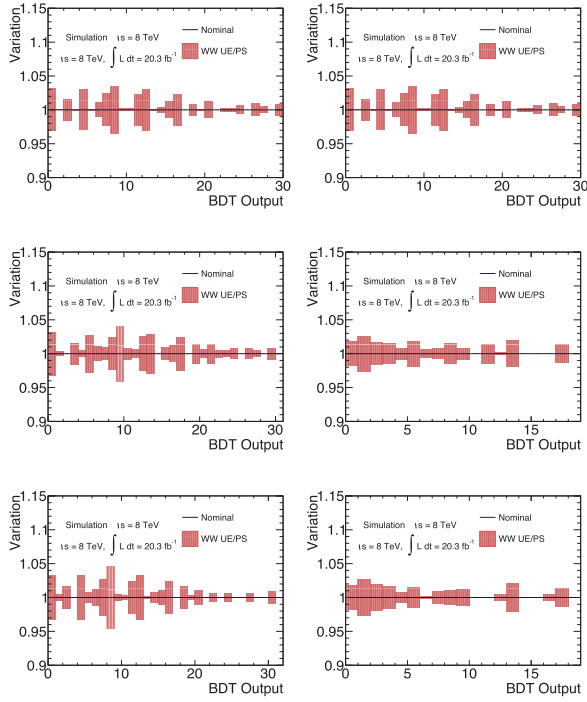


Figure 7.38: Envelope for the shape systematic uncertainty of the parton shower and underlying event modelling, around the nominal WW . The envelope is created by varying bin-by-bin the difference of `PYTHIA` and `HERWIG`. The envelopes for the spin-2 with $\kappa_g = \kappa_q$ (first row), the spin-2 with $\kappa_g = 1$, $\kappa_q = 0$ (second row) and the spin-2 with $\kappa_g = 0.5$, $\kappa_q = 1$ (third row) are shown for the 0-jet (left) and 1-jet category. For the models with non-universal couplings, the requirement on the transverse momentum of the Higgs is set to $p_T^H < 125$ GeV.

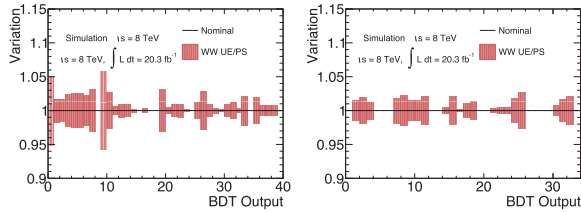


Figure 7.39: Envelope for the shape systematic uncertainty of the parton shower and underlying event modelling, around the nominal WW . The envelope is created by varying bin-by-bin the difference of `PYTHIA` and `HERWIG`. The envelopes for the CP-even (left) and CP-odd (right) final discriminants are shown.

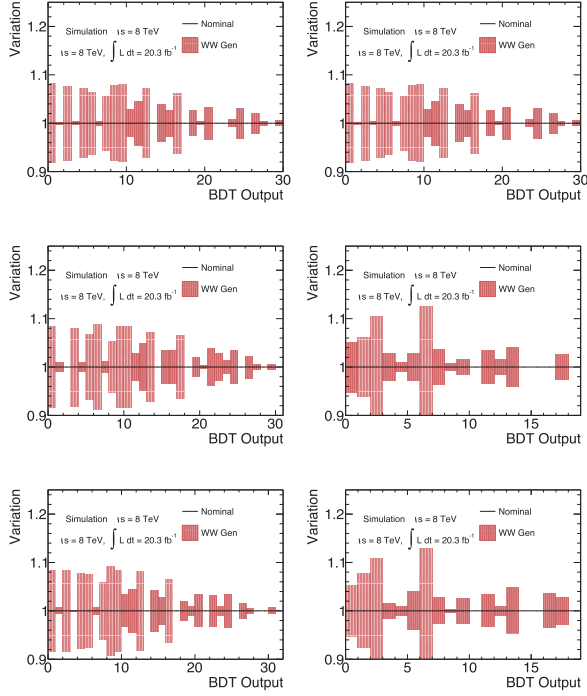


Figure 7.40: Envelope for the shape systematic uncertainty on the choice of generator modelling around the nominal WW . The envelope is created by varying bin-by-bin the difference of MC@NLO and POWHEG. The envelopes for the spin-2 with $\kappa_g = \kappa_q$ (first row), the spin-2 with $\kappa_g = 1$, $\kappa_q = 0$ (second row) and the spin-2 with $\kappa_g = 0.5$, $\kappa_q = 1$ (third row) are shown for the 0-jet (left) and 1-jet category. For the models with non-universal couplings, the requirement on the transverse momentum of the Higgs is set to $p_T^H < 125$ GeV.

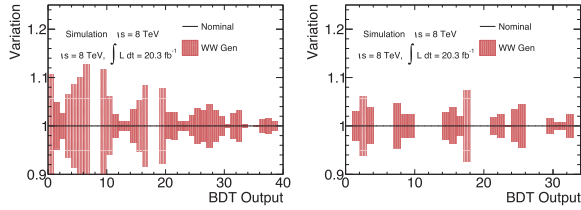


Figure 7.41: Envelope for the shape systematic uncertainty on the choice of generator modelling around the nominal WW . The envelope is created by varying bin-by-bin the difference of MC@NLO and POWHEG. The envelopes for the CP-even (left) and CP-odd (right) final discriminants are shown.

7.4 Input Variables and Discriminants in the Signal Region

Figures 7.42 and 7.43 show the distributions of the input variables in the signal region for the 0-jet category for the spin and CP analyses. The distributions are shown pre-fit, normalised to the expected event yields in the signal region. The excess of the signal is observed on top of the background-only expectation.

Similarly, Figure 7.44 shows the input variables distribution in the signal region for the 1-jet category. In this topology only the spin analysis is performed, since the CP one is restricted to the 0-jet bin.

Figure 7.45 shows the BDT0 and BDT2 output distributions in the signal regions of the 0- and 1-jet categories for the spin-2 model with universal couplings. Similar, Figure 7.46 and 7.47 show the same distributions for spin-2 models with non-universal couplings and a requirement on the Higgs transverse momentum of $p_T^H < 125$ GeV and $p_T^H < 300$ GeV respectively.

Finally, Figure 7.48 shows the BDT_{CP} distributions in the CP-even and the CP-odd case.

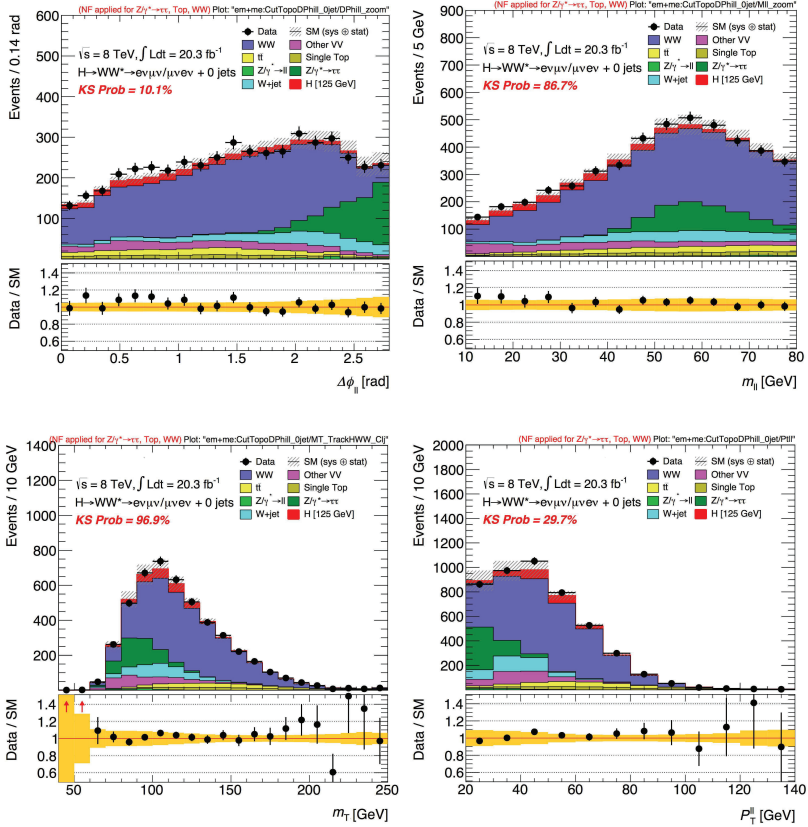


Figure 7.42: Pre-fit expected and observed distributions of the input variables of the spin analysis for the 0-jet category. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson, and it is normalised to the SM expectation. The backgrounds are normalised using scale factors from the control regions. Below each plot the ratio tests the agreement of the data with the Monte Carlo expectation. The orange band includes statistical and systematic uncertainty.

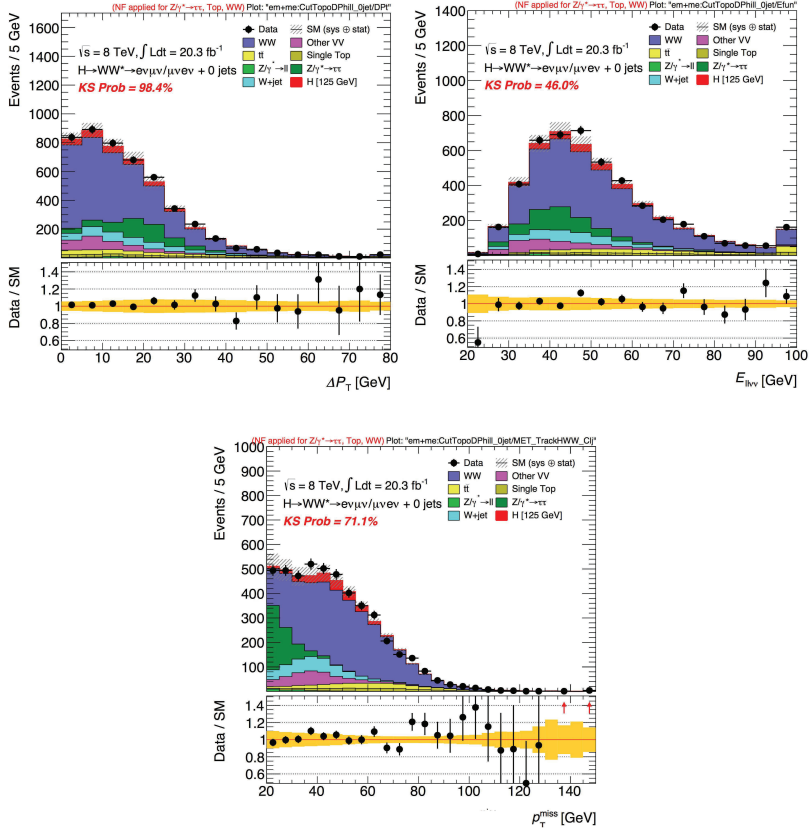


Figure 7.43: Pre-fit expected and observed distributions of the additional input variables of the CP analysis for the 0-jet category. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson, and it is normalised to the SM expectation. The backgrounds are normalised using scale factors from the control regions. Below each plot the ratio tests the agreement of the data with the Monte Carlo expectation. The orange band includes statistical and systematic uncertainty.

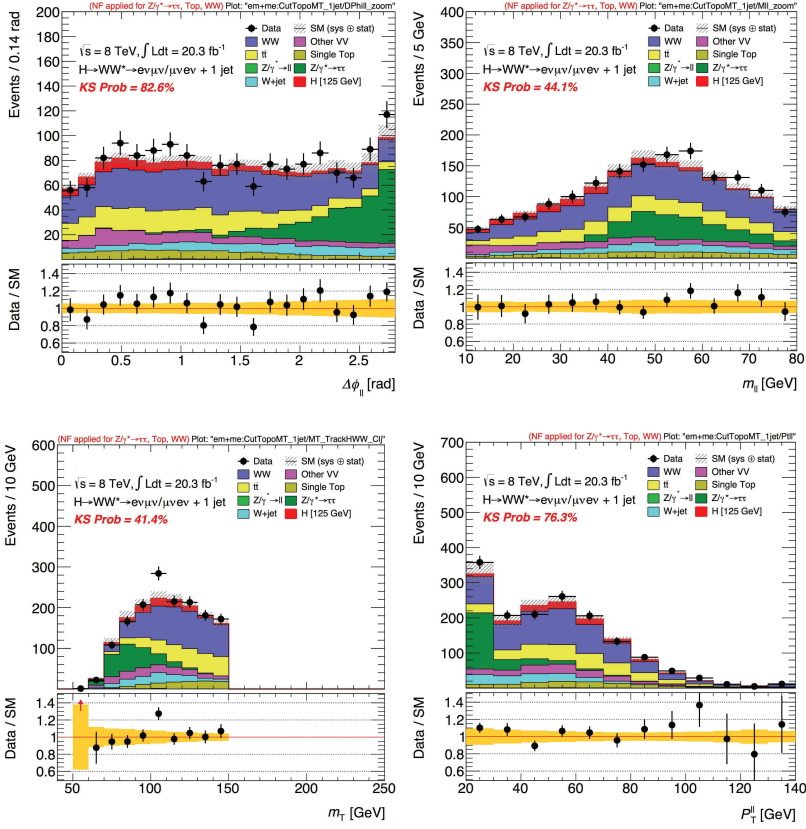


Figure 7.44: Pre-fit expected and observed distributions of the input variables of the spin analysis for the 1-jet category. The signal stacked on top of the background expectation to be compared with the data, assuming a SM Higgs boson, and it is normalised to the SM expectation. The backgrounds are normalised using scale factors from the control regions. Below each plot the ratio tests the agreement of the data with the Monte Carlo expectation. The orange band includes statistical and systematic uncertainty.

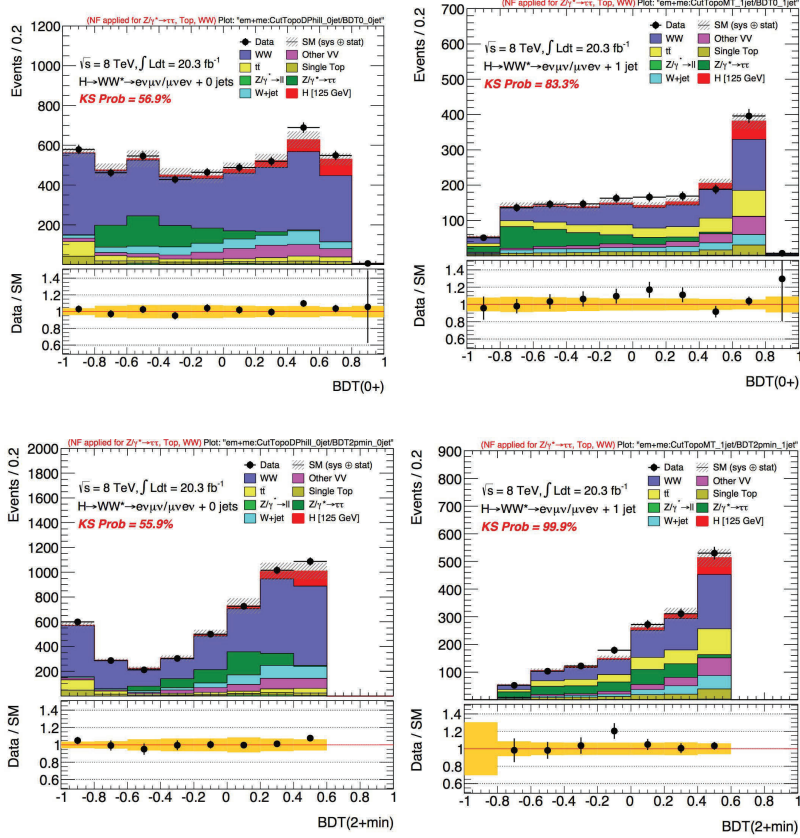


Figure 7.45: BDT0 and BDT2 output distributions in the signal region for spin-2 model with universal couplings. The plots on the left are for the 0-jet category, while the plots on the right for the 1-jet category. The normalization factors from control regions are applied. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.

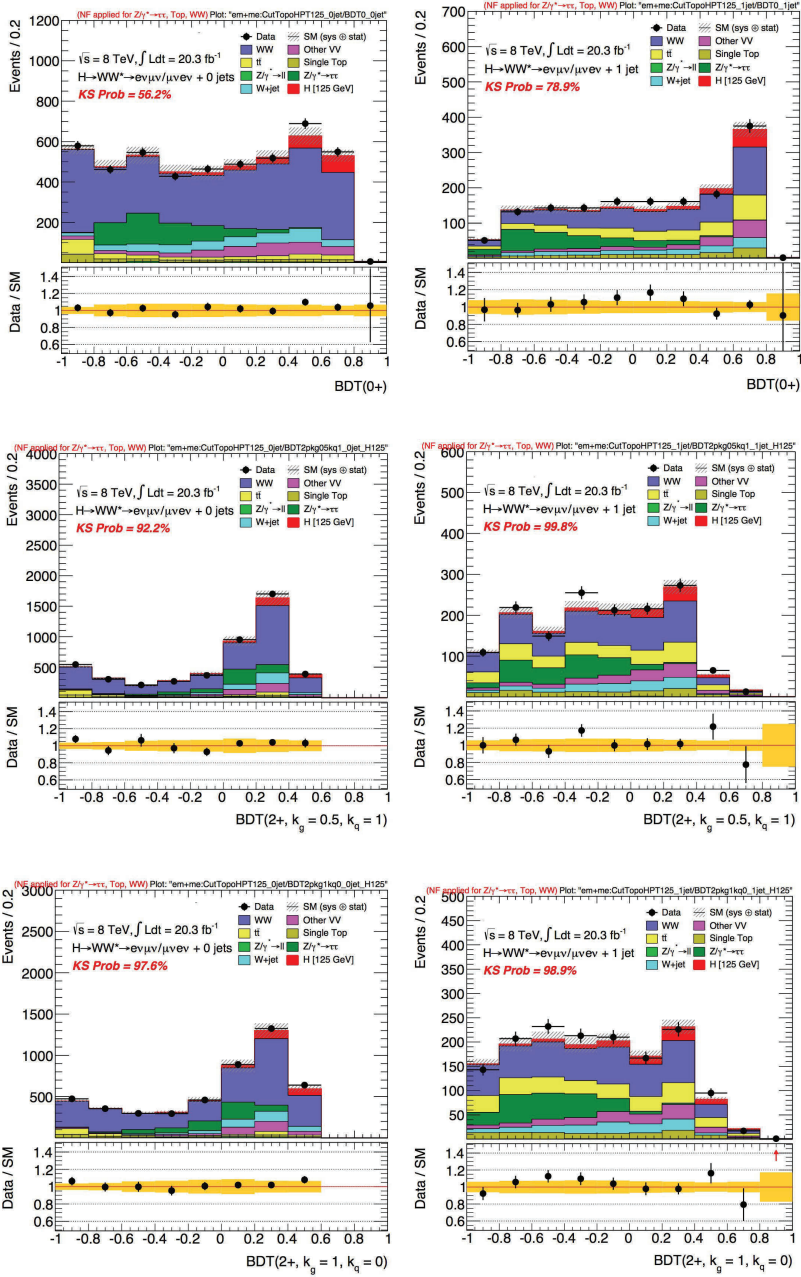


Figure 7.46: BDT0 and BDT2 output distributions in the signal region for spin-2 models with non-universal couplings and Higgs $p_T^H < 125$ GeV. The plots on the left are for the 0-jet category, while the plots on the right for the 1-jet category. The normalization factors from control regions are applied. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.

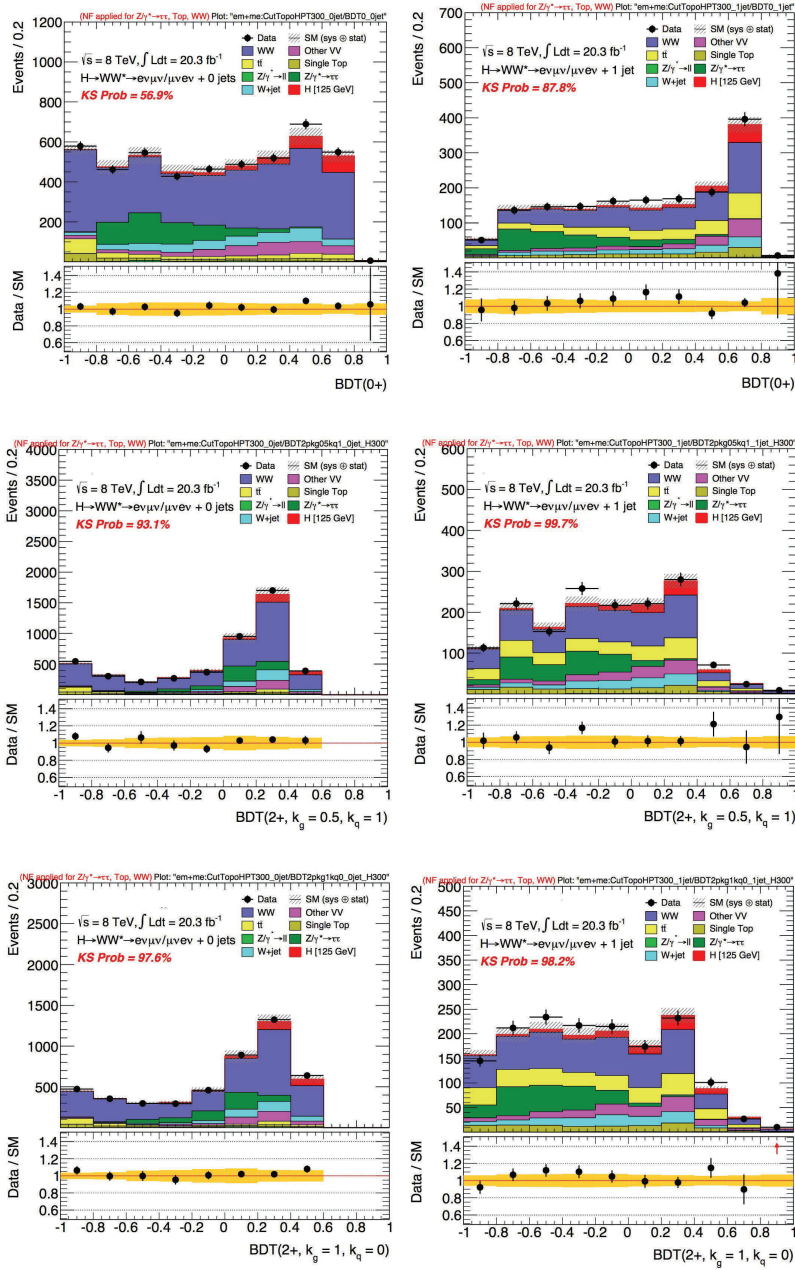
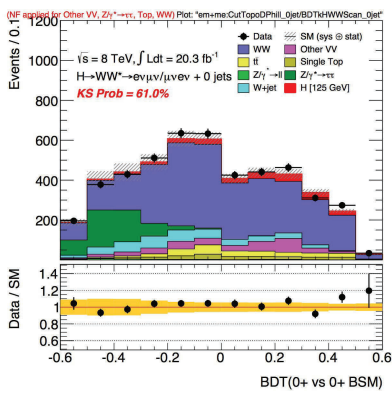
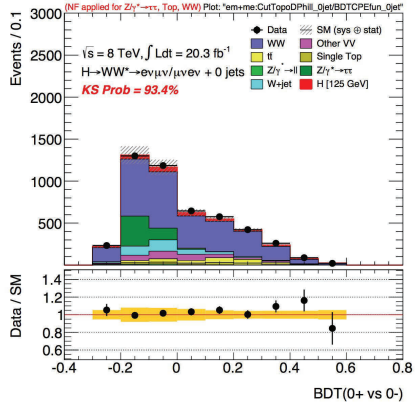


Figure 7.47: BDT0 and BDT2 output distributions in the signal region for spin-2 models with non-universal couplings and Higgs $p_T^H < 300$ GeV. The plots on the left are for the 0-jet category, while the plots on the right for the 1-jet category. The normalization factors from control regions are applied. The orange band in the bottom ratio plot represents the statistics plus systematic uncertainty band.



(a)



(b)

Figure 7.48: The output distributions in the signal region for the SM versus CP-even (a) and SM versus BSM CP-odd (b). The normalization factors from control regions are applied. The orange band in the bottom ratio plot represents the statistics plus systematics uncertainty band.

7.5 Spin Results

For the spin-2 analysis, the benchmark models have been discussed in detail in Chapter 4. In addition, the statistical treatment of the analysis is discussed in Section 7.2. The expected distributions of the test statistics q , which are derived using pseudo-experiments ($\mathcal{O}(10^5)$), are shown in Figure 7.49. The distributions for the various benchmark models are shown for the combined 0 + 1-jet categories. The CL_S calculated from these test statistics are summarised for all spin-2 benchmark models in Table 7.10. There the expected and observed sensitivities are shown for the 0- and 1-jet categories separately, as well as combined for all the spin-2 benchmark models. The SM hypothesis is favoured by the data for all the models tested. In fact, the alternative model with universal couplings is disfavoured at 84.5% confidence level, while the models with non-universal couplings are excluded at 92.5% and 99.4% confidence level.

The distributions of the best-fit values for the nuisance parameters for the spin-2 model with universal couplings are shown in Figure 7.50. The systematic on the modelling of the WW background process seems to be a bit over-constrained. Although similar behaviour has been identified also in the couplings analysis, additional cross-checks have been performed to identify if there is an impact on the final result. In detail, the impact of the systematic has been determined by comparing the result of performing the fit excluding this systematic uncertainty and the result with all the systematic uncertainties included. The impact on the expected sensitivities was found to be in average less than 3%. The constraint arises from the empty bins of the envelope around the WW nominal distribution. To further identify the impact on the result, an the average uncertainty of 3% was imposed on the empty bins. The result was compared with the default uncertainty of 0% for these bins. Pseudo-experiments were employed for this check. The final change on the expected significance for both Z_{exp}^0 and Z_{exp}^2 , where 0 and 2 are the spin hypotheses, was found to be less than 1%. Finally, a check was performed to test the behaviour of the nuisance parameter when setting the respective uncertainty for the background enriched region of the unrolled BDT output distribution to 0%. The change was found to be not large but visible. The outcome was that the background enriched bins were keeping the central value of the nuisance parameter closer to zero, while when setting the uncertainty to 0% the fit can use the WW model uncertainty to compensate the shape. This behaviour is consistent with the UE/PS uncertainty of the 2013 analysis as well as the 2014 couplings analysis.

Moreover, Tables 7.11 and 7.12 show the post-fit event yields for the SM and the alternative hypothesis for the various spin-2 benchmark models for the 0- and 1-jet category respectively.

Although the models have changed, an indirect comparison can be made between the 2013 analysis and the 2014 analysis for the spin-2 with universal couplings if restricted at the 0-jet category. The results are improved, with

the expected p_2 from 0.064 to 0.050.

Figures 7.51, 7.52 show the background subtracted plots for the spin-2 models with a p_T^H requirement at 125 GeV and 300 GeV, respectively, for the 0-jet category. The background subtracted plots are using the post-fit normalisation of the different signal hypotheses and of the different backgrounds with full systematics, to remove the backgrounds from the data distribution, and compare what is left with the post-fit normalised signal. The distribution plotted is the one dimensional unrolled BDT distribution, in which an ordering of bins have been performed. The ordering is simply done with the sole criterion of an increasing ratio of signal over background events in each bin. The data seem to better agree with the SM hypothesis.

Similarly, Figures 7.53 and 7.54 show the same plots in the 1-jet category.

channel	Z_{exp}^0	Z_{exp}^2	Z_{obs}^0	Z_{obs}^2	p_{exp}^0	p_{exp}^2	p_{obs}^0	p_{obs}^2	1-CL _s
$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 125 \text{ GeV, systematics}$									
0+1 jet	1.68 ± 0.01	2.02 ± 0.01	-0.43	2.44	0.0466	0.0215	0.6854	0.0074	97.8
0 jet	1.40 ± 0.01	1.58 ± 0.01	-0.05	1.62	0.0814	0.0576	0.5207	0.0521	89.1
1 jet	1.09 ± 0.01	1.41 ± 0.01	-0.64	2.10	0.1387	0.0791	0.7398	0.0179	93.1
$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 300 \text{ GeV, systematics}$									
0+1 jet	2.21 ± 0.01	2.66 ± 0.02	-0.06	2.71	0.0136	0.0039	0.5237	0.0034	99.3
0 jet	1.40 ± 0.01	1.58 ± 0.01	-0.06	1.63	0.0805	0.0572	0.5229	0.0511	89.3
1 jet	1.72 ± 0.01	2.29 ± 0.01	-0.23	2.54	0.0429	0.0109	0.5900	0.0055	98.7
$\kappa_g = 1, \kappa_q = 0 \ p_T < 125 \text{ GeV, systematics}$									
0+1 jet	1.74 ± 0.01	1.90 ± 0.01	0.20	1.71	0.0409	0.0287	0.4208	0.0436	92.5
0 jet	1.48 ± 0.01	1.44 ± 0.01	1.00	0.50	0.0708	0.0753	0.1584	0.3090	63.2
1 jet	1.10 ± 0.01	1.39 ± 0.01	-0.64	2.03	0.1365	0.0827	0.7380	0.0212	91.9
$\kappa_g = 1, \kappa_q = 0 \ p_T < 300 \text{ GeV, systematics}$									
0+1 jet	2.15 ± 0.01	2.64 ± 0.01	-0.13	2.78	0.0157	0.0041	0.5523	0.0027	99.4
0 jet	1.47 ± 0.01	1.44 ± 0.01	1.00	0.50	0.0733	0.0736	0.3089	0.2954	63.3
1 jet	1.54 ± 0.01	2.41 ± 0.01	-0.49	2.90	0.0587	0.0079	0.6878	0.0018	99.4
$\kappa_g = \kappa_q, \text{ systematics}$									
0+1 jet	1.76 ± 0.01	1.83 ± 0.01	0.69	1.19	0.0389	0.0334	0.2456	0.1173	84.5
0 jet	1.57 ± 0.01	1.60 ± 0.01	0.67	1.00	0.0582	0.0549	0.2525	0.1597	78.6
1 jet	1.05 ± 0.01	1.12 ± 0.01	-0.01	1.13	0.1479	0.1318	0.5048	0.1289	74.0

Table 7.10: Summary of expected and observed sensitivities for all spin-2 benchmarks.

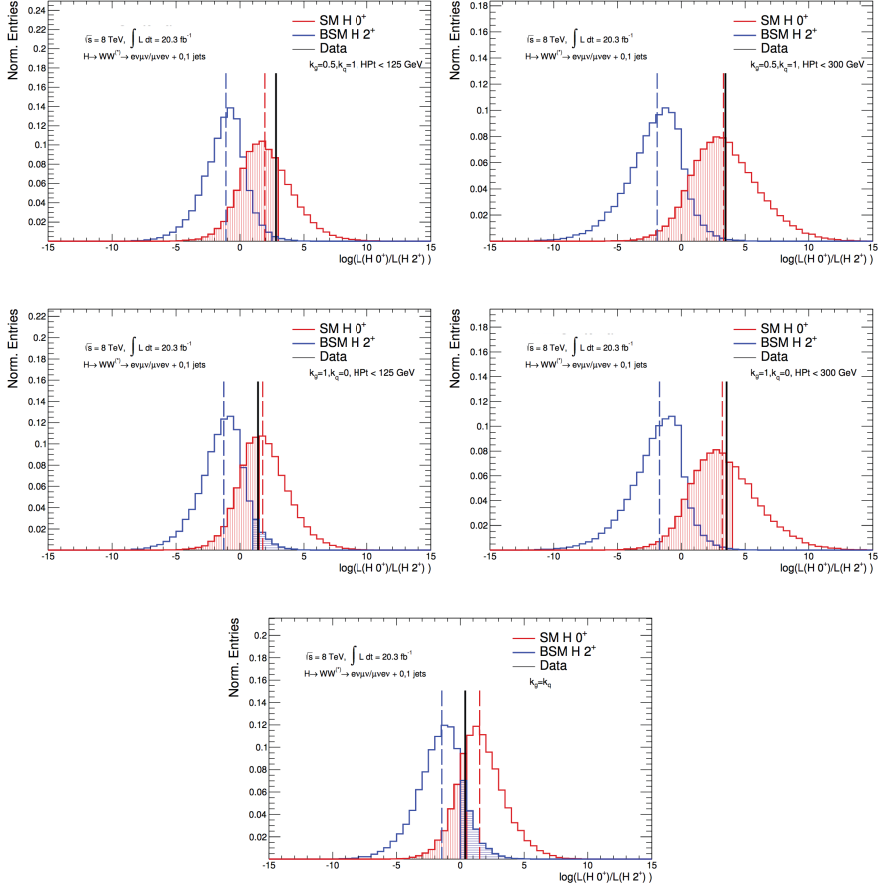


Figure 7.49: Test statistics distribution for the different spin-2 scenarios including all systematics for the 0 + 1 jets combined. First row: $\kappa_g = 0.5$ and $\kappa_q = 1$ with a cut on the Higgs boson p_T of 125 GeV (left) and 300 GeV (right). Second row: SM-like $\kappa_g = 1$ and $\kappa_q = 0$ with a cut on the Higgs boson p_T of 125 GeV (left) and 300 GeV (right). Third row: universal couplings $\kappa_g = \kappa_q$.

$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 125 \text{ GeV, systematics}$										
signal hypothesis	signal	$t\bar{t}$	single top	WW	W +jets	WZ & ZZ	$W\gamma$	$W\gamma^*$	Z_{ll}	$Z_{\tau\tau}$
SM	273.0	237.6	136.2	2887.6	365.1	86.8	91.9	138.4	40.4	470.4
ALT	299.4	238.2	136.5	2946.6	316.3	87.6	92.6	139.7	40.7	428.0
$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 300 \text{ GeV, systematics}$										
SM	272.8	238.0	136.4	2894.7	357.6	86.7	91.6	138.2	40.4	472.5
ALT	233.4	237.2	135.9	2988.8	331.6	87.8	93.2	140.7	40.8	431.6
$\kappa_g = 1, \kappa_q = 0 \ p_T < 125 \text{ GeV, systematics}$										
SM	271.9	237.5	136.1	2883.9	380.1	88.2	95.9	142.3	40.8	451.6
ALT	321.3	238.6	136.8	2922.6	322.3	88.8	95.4	142.5	41.0	418.3
$\kappa_g = 1, \kappa_q = 0 \ p_T < 300 \text{ GeV, systematics}$										
SM	266.7	238.1	136.4	2900.1	366.6	88.1	95.5	142.1	40.8	454.0
ALT	202.0	236.9	135.7	3004.8	350.2	89.3	97.4	145.1	41.3	415.8
$\kappa_g = \kappa_q, \text{ systematics}$										
SM	270.7	238.6	136.8	2903.9	369.8	85.2	87.5	132.4	39.8	463.6
ALT	358.6	241.2	138.2	2914.7	304.7	85.1	87.1	132.5	39.2	426.3

Table 7.11: Post-fit event yields for all spin-2 benchmarks for the 0-jet case in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel.

$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 125 \text{ GeV, systematics}$										
signal hypothesis	signal	$t\bar{t}$	single top	WW	W +jets	WZ & ZZ	$W\gamma$	$W\gamma^*$	Z_{ll}	$Z_{\tau\tau}$
SM	94.1	246.3	93.8	579.9	121.5	54.1	26.7	41.5	5.8	232.1
ALT	103.3	246.8	94.6	599.7	105.5	54.7	27.1	44.0	5.8	210.6
$\kappa_g = 0.5, \kappa_q = 1 \ p_T < 300 \text{ GeV, systematics}$										
SM	95.7	253.5	95.7	615.5	120.6	55.6	27.4	44.1	5.8	234.2
ALT	82.0	251.5	95.0	647.9	111.9	56.4	28.2	49.3	5.8	216.7
$\kappa_g = 1, \kappa_q = 0 \ p_T < 125 \text{ GeV, systematics}$										
SM	93.3	245.2	93.5	574.7	126.2	54.9	27.2	42.8	5.8	234.1
ALT	110.9	245.8	94.3	591.0	107.5	55.2	27.3	43.7	5.8	215.0
$\kappa_g = 1, \kappa_q = 0 \ p_T < 300 \text{ GeV, systematics}$										
SM	93.2	254.8	96.8	608.2	123.6	56.4	28.1	46.3	5.8	236.3
ALT	70.9	251.5	95.3	646.3	118.0	57.3	28.9	52.2	5.8	219.8
$\kappa_g = \kappa_q, \text{ systematics}$										
SM	95.3	257.4	97.5	607.2	124.4	54.9	27.3	45.1	5.7	233.3
ALT	125.9	261.5	100.5	604.1	103.3	55.0	27.4	46.1	5.7	223.2

Table 7.12: Post-fit event yields for all spin-2 benchmarks for the 1-jet cases in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel

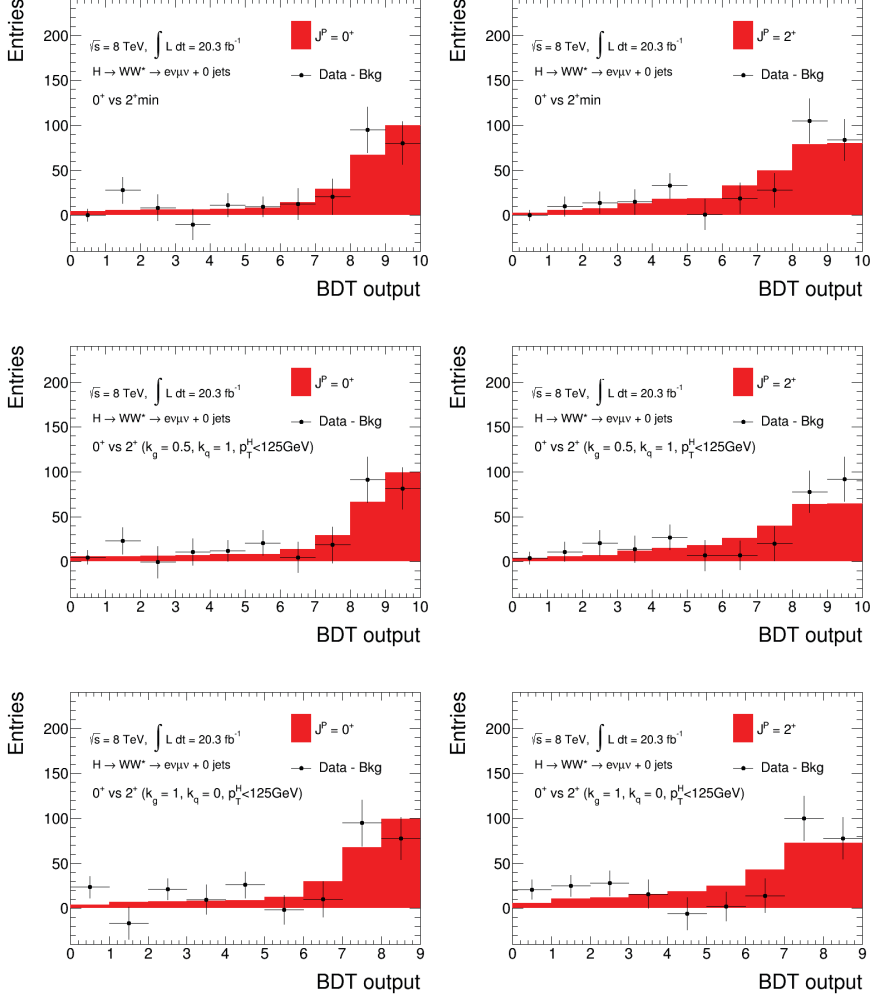


Figure 7.51: The unrolled one-dimensional BDT output after background subtraction and using post-fit normalisation for the universal couplings $\kappa_g = \kappa_q$ (first row) in the 0-jet channel, the $\kappa_g = 0.5$ and $\kappa_q = 1$ with a selection on the Higgs boson p_T of 125 GeV (middle row) and for the $\kappa_g = 1$ and $\kappa_q = 0$ with a selection on the Higgs boson p_T of 125 GeV (bottom row). The left column shows the SM Higgs signal hypothesis, while the right column shows the alternative hypothesis.

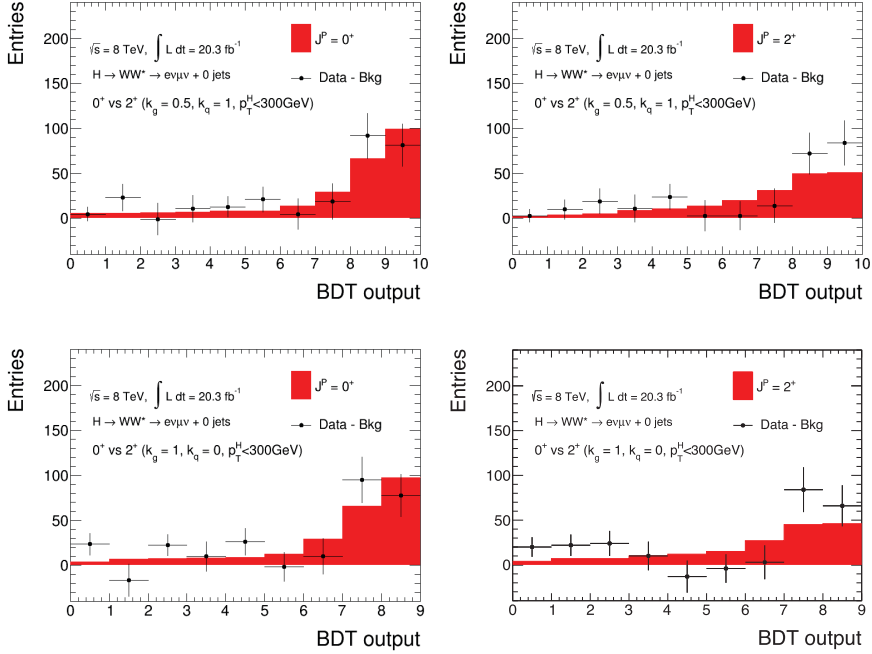


Figure 7.52: The unrolled one-dimensional BDT output after background subtraction and using post-fit renormalisation in the 0-jet channel for the $\kappa_g = 0.5$ and $\kappa_q = 1$ with a selection on the Higgs boson p_T of 300 GeV (top row) and for the $\kappa_g = 1$ and $\kappa_q = 0$ with a selection on the Higgs boson p_T of 300 GeV (bottom row). The left column shows the SM Higgs signal hypothesis, while the right column shows the alternative hypothesis.

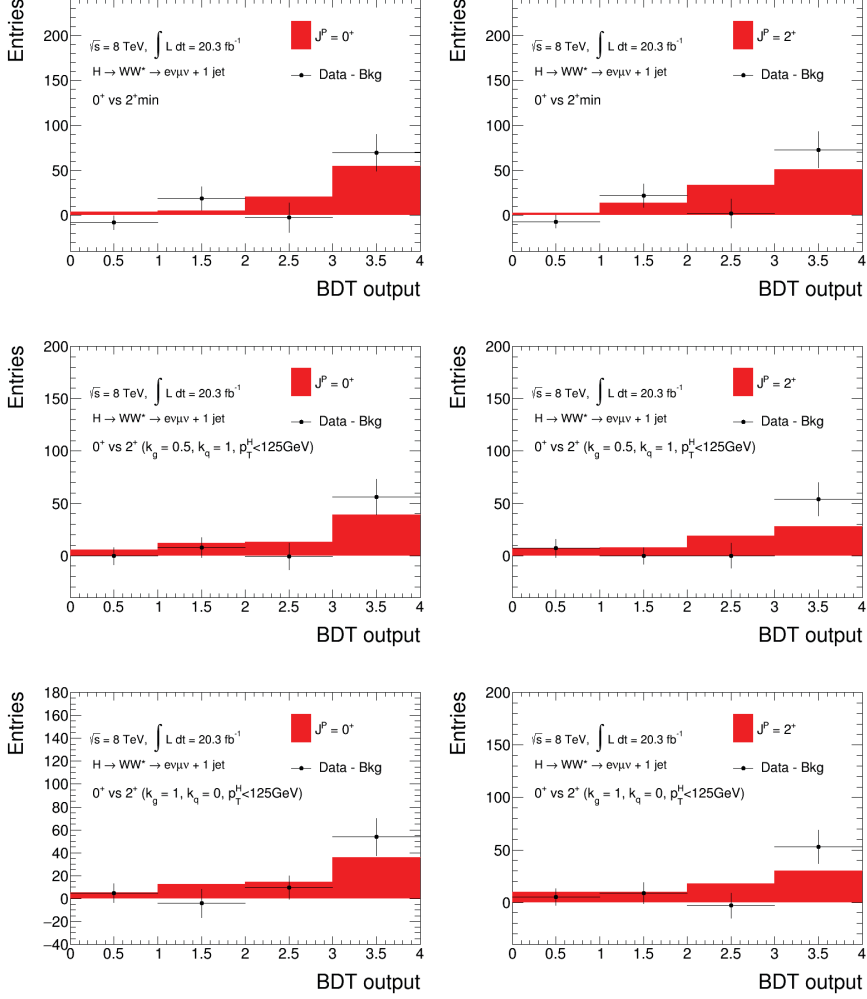


Figure 7.53: The unrolled one-dimensional BDT output after background subtraction and using post-fit renormalisation for the universal couplings $\kappa_g = \kappa_q$ (first row) in the 1-jet channel, the $\kappa_g = 0.5$ and $\kappa_q = 1$ with a selection on the Higgs boson p_T of 125 GeV (middle row) and for the $\kappa_g = 1$ and $\kappa_q = 0$ with a selection on the Higgs boson p_T of 125 GeV (bottom row). The left column shows the SM Higgs signal hypothesis, while the right column shows the alternative hypothesis.

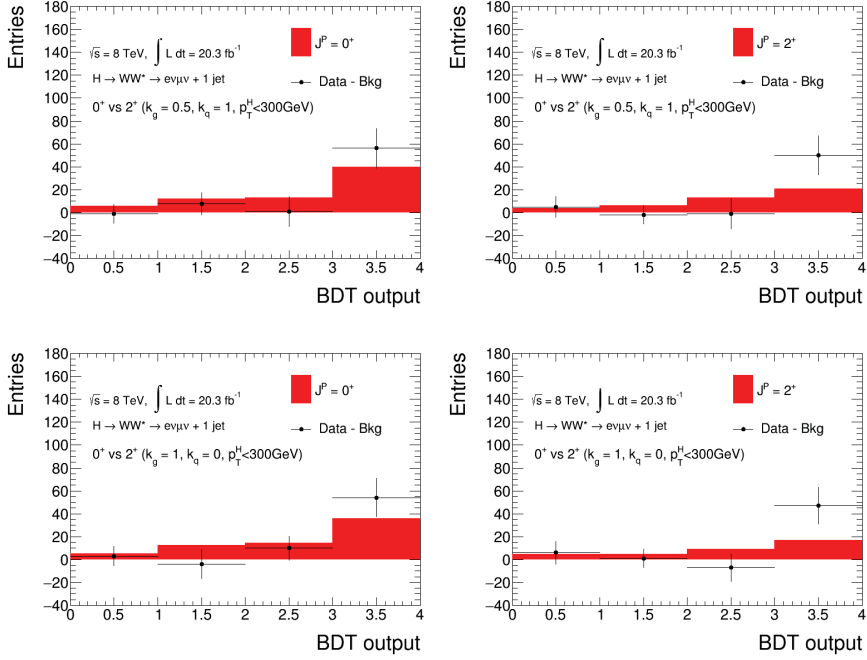


Figure 7.54: The unrolled one-dimensional BDT output after background subtraction and using post-fit normalisation in the 1-jet channel for the $\kappa_g = 0.5$ and $\kappa_q = 1$ with a selection on the Higgs boson p_T of 300 GeV (top row) and for the $\kappa_g = 1$ and $\kappa_q = 0$ with a selection on the Higgs boson p_T of 300 GeV (bottom row). The left column shows the SM Higgs signal hypothesis, while the right column shows the alternative hypothesis.

7.6 Spin-0 and CP-mixing Results

The procedure to test the compatibility of the CP-mixed signal with the observed data has been discussed in Section 7.2 and the benchmark models in Chapter 4.

7.6.1 Fixed Hypothesis Tests

For the fixed hypothesis test of the SM against the pure BSM CP-even and pure BSM CP-odd case, the distributions of the test statistics q , derived from pseudo-experiments, are shown in Figure 7.55. These distributions are symmetric and have no overflow or underflow bins. The expected and observed significances and CL_S estimators are summarised in Table 7.13. In addition, the distributions of the best-fit values for the nuisance parameters for the CP-even (CP-odd) study are shown in Figure 7.56 (Figure 7.57). The WW modelling nuisance parameter has a similar behaviour as observed for the spin analysis (Section 7.5). The impact on the expected sensitivity, as well as on the final result was found to be even smaller than the one observed in the spin analysis. Finally, the data are disfavouring the BSM CP-even scenario in favour of the SM one at 70.8% confidence level. Furthermore, the data exclude the BSM CP-odd scenario at 96.5% confidence level. Figure 7.58 shows the background subtracted plots for the SM against the CP-even and CP-odd fixed hypothesis test.

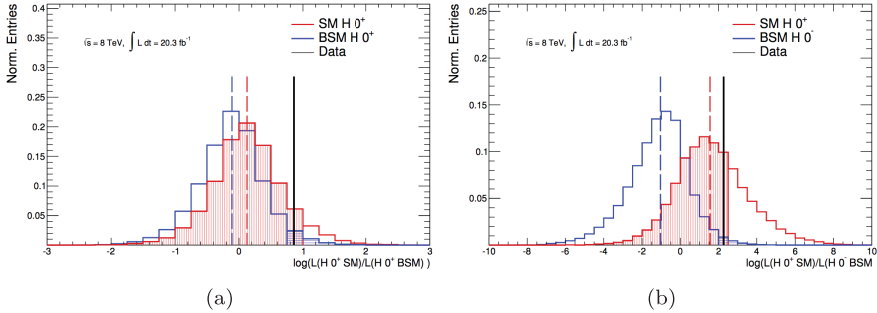


Figure 7.55: Test statistic distribution for the CP-even (a) and CP-odd (b) scenario including all systematics for the 0-jet channel.

channel	Z_{exp}^0	Z_{exp}^2	Z_{obs}^0	Z_{obs}^2	p_{exp}^0	p_{exp}^2	p_{obs}^0	p_{obs}^2	1 - CL _s
<i>BSM CP-odd, systematics</i>									
0 jet	1.54 ± 0.01	1.85 ± 0.01	-0.39	2.25	0.0620	0.0319	0.6521	0.0122	96.5%
<i>BSM CP-even systematics</i>									
0 jet	0.50 ± 0.01	0.56 ± 0.01	-1.32	1.92	0.3099	0.2866	0.9067	0.0273	70.8%

Table 7.13: Summary of expected and observed sensitivities for the SM versus pure BSM CP-odd and and CP-even cases.

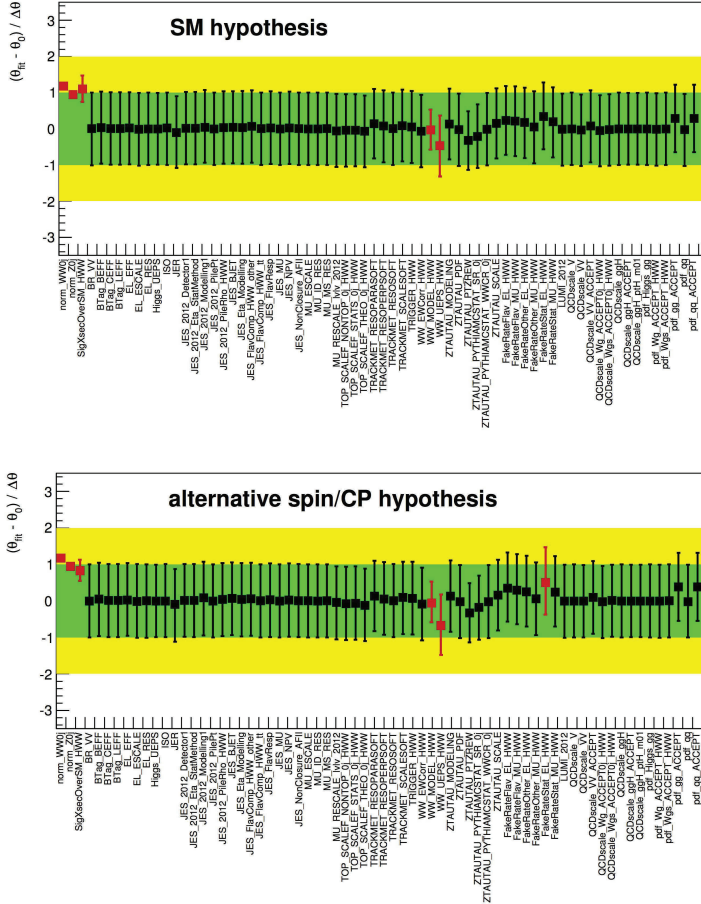


Figure 7.56: The distribution of the best-fit values for the nuisance parameters of the CP-even study. The SM (top) and the alternative hypothesis (bottom) are tested against the observed data.

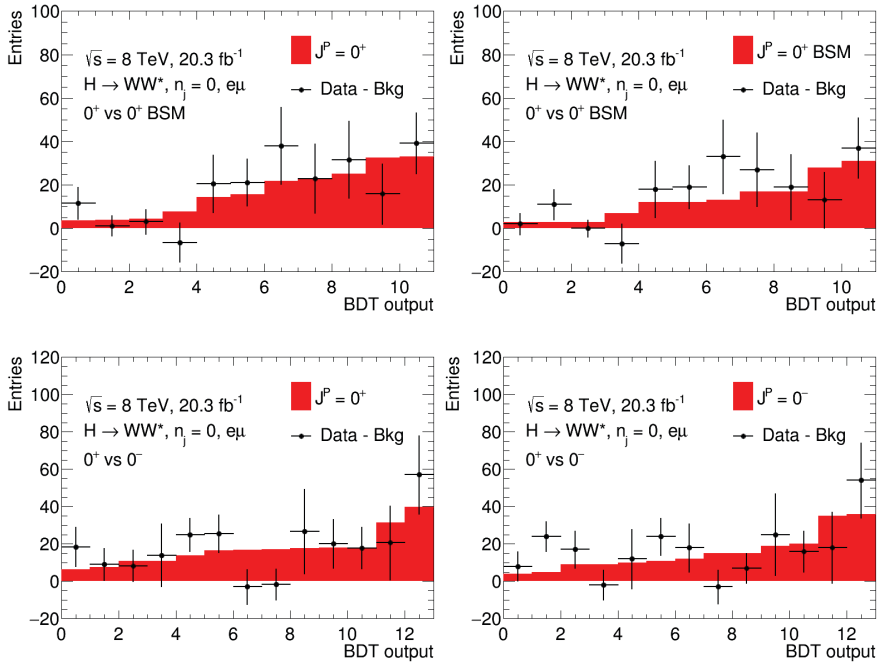


Figure 7.58: The unrolled one-dimensional BDT output after background subtraction and using post-fit renormalisation in the 0-jet channel for the CP-even (top row) and the CP-odd (bottom row). The left column shows the SM Higgs signal hypothesis, while the right column shows the alternative hypothesis.

7.6.2 CP Mixing Scans

In addition, for the CP-mixing results the CP-even and CP-odd scans are shown in Figure 7.59. As far as the CP-even scan is concerned, the expected sensitivity is low except for the region around -1 . This behaviour is explained by an interference between the SM amplitude and the BSM CP-even one. The Lagrangian for the spin-0 Higgs sector, where the Higgs decays into a pair of W is given by

$$\mathcal{L}_0^W = \left\{ c_\alpha \kappa_{\text{SM}} [g_{HWW} W_\mu^+ W^{-\mu}] - \frac{1}{2} \frac{1}{\Lambda} [c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}] \right\} X_0. \quad (7.2)$$

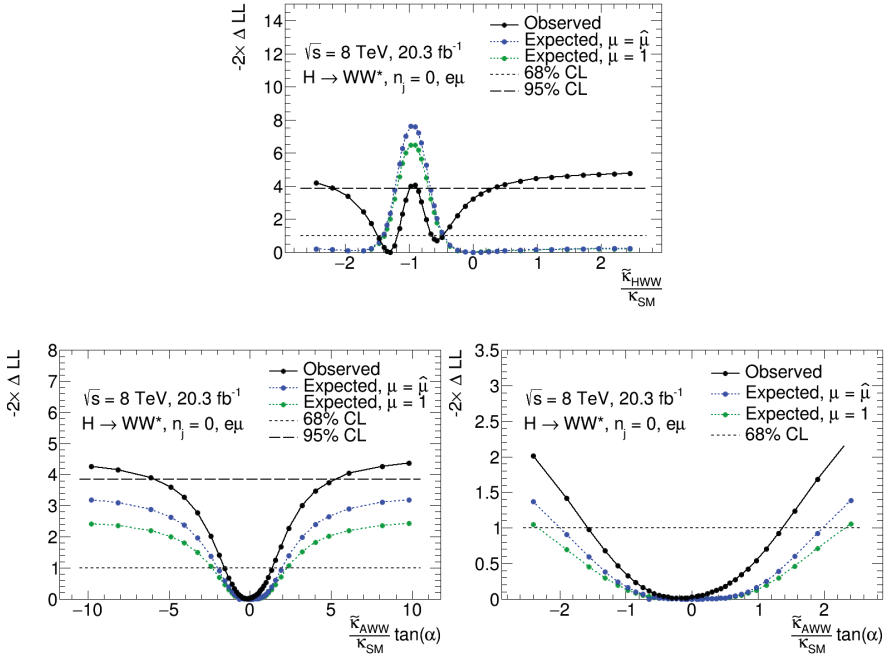


Figure 7.59: The CP-even mixing scan result (top) and the CP-odd mixing scan result (bottom). The lower right plot corresponds to a selected sub-range of the scan axis around the minimum.

In Equation 7.2, assuming that $c_\alpha = \kappa_{\text{SM}} = 1$, the term $g_{HWW} W_\mu^+ W^{-\mu}$ is cancelled by $\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu}$ for a specific κ_{HWW} value. This value is dependent on the product of the four-vectors of the W bosons. The same behaviour is also expected in the other channels, e.g. the $H \rightarrow ZZ^* \rightarrow 4\ell$

decay, but the value of κ_{HWW} that will result in the cancellation of amplitudes should be slightly different due to the difference in the invariant mass of the Z bosons with respect to the W ones. This interference results to a change on the shape of the input BDT variables. This change is shown for the $\Delta\phi_{\ell\ell}$ variable in Figure 7.60. In this figure, the shapes of the simulated SM Higgs signal, the simulated signals with various $\frac{\kappa_{\text{HWW}}}{\kappa_{\text{SM}}} = \kappa$ values, as well as the sum of background processes are shown. While changing the value for the κ , for $\kappa > 0$ (Figure 7.60a), only small variations are observed between the different alternative signals, when scanning the $\kappa < 0$ axis, the shapes of the alternative signal starting from more "SM signal-like" ones, are shifted to be background-like for values around $\kappa = 1$ and then shift back to be more signal-like for smaller values of κ . This behaviour results in a widely increased sensitivity for the range of κ values between -0.5 and -1.3 , and also explains why the observed result shows two, roughly symmetric, minima.

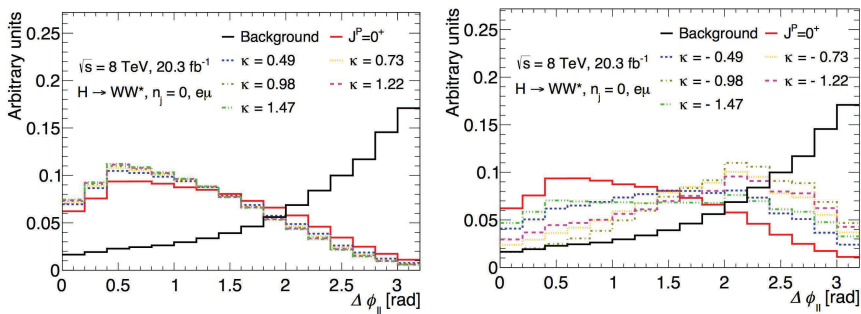


Figure 7.60: Expected Higgs-boson $\Delta\phi_{\ell\ell}$ distribution normalised to unit area. The distributions are shown for the SM hypothesis (solid red line) and the sum of all backgrounds (solid black). The dashed lines correspond to positive (left) and negative (right) values of the CP-even scan.

The post-fit event yields for the CP analysis benchmarks are summarised in Table 7.14.

<i>SM versus BSM CP-odd, systematics</i>										
signal hypothesis	signal	$t\bar{t}$	s. top	WW	W+jets	WZ & ZZ	$W\gamma$	$W\gamma^*$	Z_{ll}	$Z_{\tau\tau}$
SM	264.1	234.0	134.1	2881.7	398.0	86.8	91.5	138.8	40.4	455.9
ALT	234.9	234.8	134.5	2917.8	386.7	87.8	95.1	142.4	40.5	447.0
<i>SM versus BSM CP-even, systematics</i>										
SM	240.9	233.3	133.7	2907.0	411.7	85.6	88.4	134.9	40.1	446.0
ALT	181.7	232.1	133.0	2933.4	438.9	85.6	89.1	135.5	40.0	447.4

Table 7.14: Post-fit event yields for all CP benchmarks for the 0-jet case.

Finally, for this scan, the $\kappa = \frac{\tilde{\kappa}_{\text{HWW}}}{\kappa_{\text{SM}}}$ values above 0.4, below -2.2 , as well

as in the region between -0.85 and 1.0 can be excluded at 95% confidence level. The values above -0.5 and below -1.5 , as well as between -1.2 and -0.65 can be excluded at 68% confidence level. Finally, the observed minimum of the $-2\Delta LL$ distribution is at -1.3 , which is compatible with the SM within 1.9 standard deviations.

On the other hand, for the CP-odd scan, values of the $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}}$ above 5.0 and -6.0 can be excluded at 95% confidence level. Values above 1.3 and -1.6 are disfavoured at 68% confidence level. While the expected and observed distributions are slightly asymmetric around the SM-like minimum of 0, the sensitivity to the sign of the scan parameter is low. A broad minimum at -0.2 of the $-2\Delta LL$ distribution is observed, compatible with the SM within 0.5 standard deviations.

7.6.3 CP-mixing analysis scan tests

The results of the CP-mixing analysis have undergone several validation studies. Tests have been done to study and understand the CP-mixing scan results.

Two injection tests have been performed to validate that the statistical interpretation of the result is handled properly. Two pseudo-data sets have been produced using the Asimov expectation under the assumption that the $\tilde{\kappa}_{HWW}$ values are set to the values of the two observed minima, $\tilde{\kappa}_{HWW} = -0.56$ and -1.29 . The nuisance parameters have been fixed to their post-fit values and the whole CP-even scan is repeated using as data the two pseudo-data sets. The result is shown in Figure 7.61. The curves for the Asimov data sets have a shape close to the observed distribution as expected and the two minima are reproduced. In addition, the observed minima are asymmetric, both in the real data case, as well as in the pseudo-data one. In the case of data, the two minima are at -1.29 and -0.56 , with the former to be deeper with respect to the latter. The asymmetry of the minima is attributed to fluctuations of the data in some bins.

The second test is performed by employing pseudo-experiments. Using the SM fit to the data distributions, pseudo-experiments (i.e. "toy" datasets) have been generated. For each of the toy datasets the full scan of the $\tilde{\kappa}_{HWW}$ parameter was performed. The post-fit BDT output distribution in the signal region is shown in Figure 7.62a, while Figure 7.62b, shows the ratio of the BDT output as taken from some selected toy datasets, compared to the Asimov dataset. The toy datasets show up to 2σ fluctuations with respect to the Asimov. The 1σ and 2σ bands on the plot, correspond to the statistical uncertainty.

In addition, the pseudo-experiments generated around the expected SM $\tilde{\kappa}_{HWW} = 0$ value were used to verify the one and two standard deviations lines, expected from the asymptotic approximation. Since this approximation is followed for the CP mixing scans and no pseudo-experiments are used for the final result, the definition of the confidence level lines at 68% and 95% CL_S have to be validated. Therefore, few hundreds of pseudo-experiments

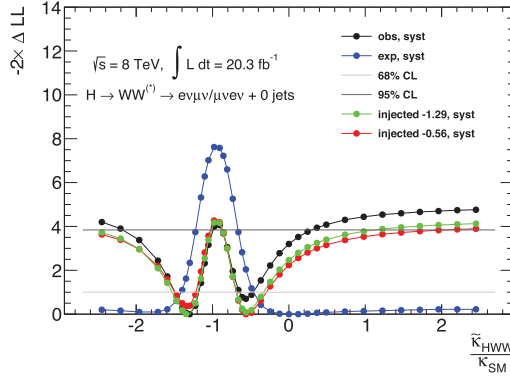


Figure 7.61: The CP-even scan using data and two post-fit asimov data sets for $\tilde{\kappa}_{HWW} = -0.56$ and -1.29 scan points.

have been performed around the SM value and the scan has been redone for each pseudo-experiment. The pseudo-experiment curves show that

- the expected SM curve is reproduced
- they are similar to the observed curve, having two minima, one of which is deeper than the other.

In addition, $\approx 70\%$ of the pseudo-experiments are below the 1σ line, while a $\approx 30\%$ are between the 1σ and the 2σ lines. These results are summarised on Figure 7.63, on which two sets of toy-datasets generated around the SM are presented.

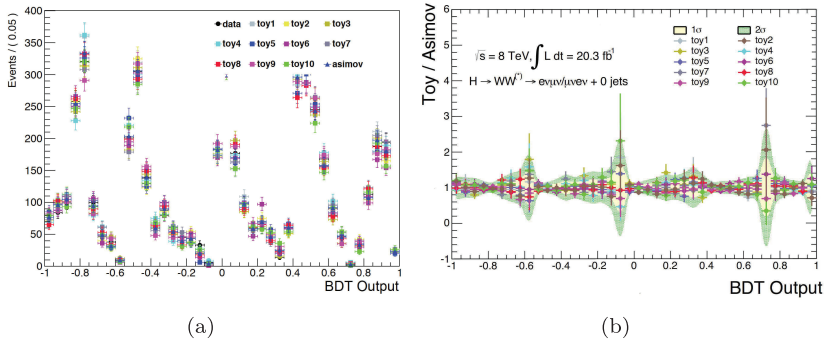


Figure 7.62: (a) Post-fit BDT output distribution in the signal region for pseudo-datasets generated around the SM. (b) Ratio of the BDT distributions acquired by various pseudo-experiments generated around the SM value, over the Asimov BDT distribution. The yellow and green bands represent the 1σ and 2σ uncertainties calculated using the data statistics. Some toy distributions show fluctuations $\approx 2\sigma$ with respect to the Asimov.

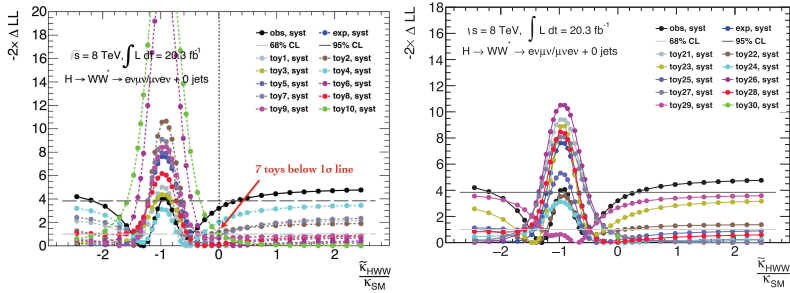


Figure 7.63: The CP-even scan for 20 selected toy datasets generated around the SM value. The two minima are reproduced with similar structure as in the observed data. In addition, the number of scan curves below the estimated (from the asymptotic approximation) 1σ line, as well as between the 1σ and 2σ lines are consistent with the expectation.

7.7 Combination with $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$

The results for the spin and CP studies from $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ have been combined with the results of other two diboson decay mode analyses performed in ATLAS, $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ [154]. For the spin-2 analysis, all three decay modes combine their individual results, testing the same benchmark models that are discussed in Chapter 4. The signal modelling for the spin-2 analysis is based on the EFT approach for all decay channels.

On the other hand, in the combination of the CP and CP-mixing analysis,

only the $H \rightarrow WW^*$ and the $H \rightarrow ZZ^*$ channels contribute. Contrary to the EFT approach followed by the analysis presented in detail in this thesis, the $H \rightarrow ZZ^*$ channel uses the anomalous couplings approach, discussed in Chapter 4. The same matrix element re-weighting technique is followed, where all the mixed CP-hypotheses are obtained by re-weighting a signal sample generated with $g_1 = 1$, $g_2 = 1 + i$, $g_4 = 1 + i$. The combination is performed by using the mapping between the two approaches that have been developed, which is also discussed in Chapter 4.

In terms of discriminants, the $H \rightarrow \gamma\gamma^*$ channel uses the separating power of the production opening angle of the two photons in the Collins-Soper frame, $|\cos\theta^*|$, and the transverse momentum of the diphoton system, $p_T^{\gamma\gamma}$. The distributions of both variables are split into 10 equal bins of $|\cos\theta^*|$ for $p_T^{\gamma\gamma} < 125$ GeV, while the 11th bin contains all events with $125 < p_T^{\gamma\gamma} < 300$ GeV. The final fit discriminant is the mass of the diphoton system. On the other hand, the $H \rightarrow ZZ^*$ decay mode uses the Cabibbo-Maksymowicz variables in a matrix-element based likelihood ratio, named $J^P - \text{MELA}$. The fit discriminant is the two-dimensional distribution of the BDT response trained to separate the signal from the ZZ^* continuum background, and the $J^P - \text{MELA}$ response.

For the statistical combination, a similar likelihood as for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ study is constructed that depends on the spin-parity assumption of the signal. The likelihood is a product of the conditional probabilities over the binned discriminant distributions in each channel:

$$\mathcal{L}(\text{data}|J^P, \mu, \vec{\theta}) = \prod_j^{N_{\text{chan}}} \prod_i^{N_{\text{bins}}} P(N_{i,j}|\mu_j \cdot S_{i,j}^{(J^P)}(\vec{\theta}) + B_{i,j}(\vec{\theta})) \times \mathcal{A}_j(\vec{\theta}), \quad (7.3)$$

where μ_j represents the signal rate normalised to the SM prediction in each channel, and $\vec{\theta}$ represents all the nuisance parameters. The likelihood function is the product of Poisson distributions P that correspond to the observed $N_{i,j}$ events, where $S_{i,j}^{(J^P)}$ and $B_{i,j}$ are the estimated signal and background events in each bin. Furthermore, in order to be insensitive to the Higgs boson couplings, the signal yields per hypothesis are treated as independent parameters in the likelihood definition. These parameters enter into the final fit. The test statistic used for the combined results is the same as the one discussed in Section 7.2.

The results of the fixed hypothesis tests are presented in terms of the CL_S estimator. On the other hand, the CP mixing results are presented in terms of the $-2\Delta LL$ distribution. Table 7.15 shows the results for the fixed hypothesis testing for the spin benchmark models and the pure CP-states scenarios. The observed CL_s estimators for the alternative hypotheses are shown. The observed data for all the tested benchmark models are in favour of the SM predictions.

In addition, for the CP scans, Table 7.16 shows the expected and observed best-fit values for the two channels separately and their combined result. Furthermore, in the same table, the range of the scan parameter which yields at least 95% CL rejection of the non-SM scenario, is shown. The results are summarised in Figure 7.64. In this figure, the expected and observed distributions of the test statistics for the BSM CP-even and BSM CP-odd scans are shown. The observed distributions are shown separately for the two channels, as well as their combination. On the other hand, the combined expected distributions are shown using the SM signal strength, as well as the best-fit one. For both scans the value of 0.0 of the respective scan parameter corresponds to the pure SM case. The observed best-fit values for the combined results are $\tilde{\kappa}_{HVV}/\kappa_{\text{SM}} = 0.48$ and $(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha = 0.68$. As expected, the two CP scans show a similar behaviour to what was observed in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ case. The best-fit values for both scan are not exactly at the SM expected value, although they are compatible with it within the statistical uncertainty.

Tested Hypothesis	$p_{exp,\mu=1}^{ALT}$	$p_{exp,\mu=\hat{\mu}}^{ALT}$	p_{obs}^{SM}	p_{obs}^{ALT}	Obs. CL _S (%)
BSM 0 ⁺	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
BSM 0 ⁻	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+, \kappa_g = kq$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+, \kappa_g = 1, kq = 0; p_T^H < 300 \text{ GeV}$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+, \kappa_g = 1, kq = 0; p_T^H < 125 \text{ GeV}$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+, \kappa_g = 0.5, kq = 1; p_T^H < 300 \text{ GeV}$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+, \kappa_g = 0.5, kq = 1; p_T^H < 125 \text{ GeV}$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Table 7.15: Expected and observed p -values for the different fixed hypothesis test performed with the combined workspaces of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. For each test, the observed CL_S for the alternative hypothesis is quoted in the last column. The data are in favor of the SM for all benchmark models tested.

Coupling ratio	Best fit value		95% CL Exclusion Regions	
	Expected	Observed	Expected	Observed
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$				
$\tilde{\kappa}_{HVV}/\kappa_{\text{SM}}$	0.0	-1.3	$[-1.2, -0.7]$	$(-\infty, -2.2] \cup [-1.0, -0.85] \cup [0.4, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha$	0.0	-0.2	-	$(-\infty, -6] \cup [5, \infty)$
$H \rightarrow ZZ^* \rightarrow 4\ell$	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\text{SM}}$	0.0	-0.2	$(-\infty, -0.75] \cup [6.95, \infty)$	$(-\infty, -0.75] \cup [2.45, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha$	0.0	-0.8	$(-\infty, -2.95] \cup [2.95, \infty)$	$(-\infty, -2.85] \cup [0.95, \infty)$
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\text{SM}}$	0.0	-0.48	$(-\infty, -0.55] \cup [4.80, \infty)$	$(-\infty, -0.73] \cup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha$	0.0	-0.68	$(-\infty, -2.33] \cup [2.30, \infty)$	$(-\infty, -2.18] \cup [0.83, \infty)$

Table 7.16: Expected and observed best-fit values for the tensor structure terms of $\tilde{\kappa}_{HVV}/\kappa_{\text{SM}}$ and $(\tilde{\kappa}_{AVV}/\kappa_{\text{SM}}) \cdot \tan\alpha$ for the BSM CP-even and BSM CP-odd scans, respectively. The values are shown separately for $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow ZZ^* \rightarrow 4\ell$, as well as their combination. The expected values are produced for the signal strength measured in data, while assuming the best-fit values for all the nuisance parameters. Signal strengths are treated independently per decay channel and center-of-mass energy.

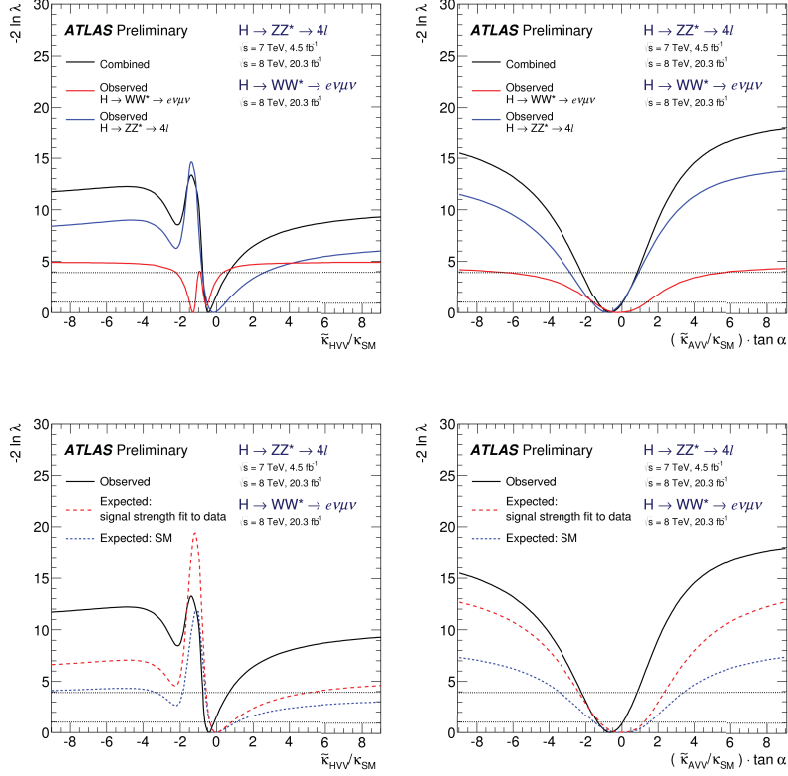


Figure 7.64: Top row: Observed distributions of the test statistics for the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow ZZ^* \rightarrow 4l$, as well as their combination, for the BSM CP-even (left) and BSM CP-odd (right) scans. Bottom row: The distributions of the test statistics for the observed combined, as well as the expected one. The latter is plotted under the assumption of the SM signal strength, as well as the best-fit (obtained from the fit to the data) signal one. The two lines correspond to the 68% ($-2 \ln \lambda = 1.0$) and 95% ($-2 \ln \lambda = 3.84$) confidence level [154].

7.8 Summary

To summarise, the results presented in this chapter are the legacy results for the Run-I data of the ATLAS detector for the spin and CP properties of the newly discovered Higgs boson. The data so far are strongly favouring the spin-0 nature of the boson. Small deviations from the pure SM hypothesis are observed as far as the CP properties are concerned, but are comfortably compatible with the SM expectations, within the measurement uncertainties. Coming back to the question asked in the first chapter, on whether the observed resonance is the SM Higgs boson, from the perspective of its spin and CP properties one can conclude that it is indeed a scalar boson, since the alternative spin-1[±] and spin-2⁺ hypotheses have been excluded. For the CP properties, the data seem to indicate that it is indeed a CP-even scalar, although the possibility of mixed CP states is not yet fully excluded. This makes the Run-II era of the LHC and ATLAS even more exciting for the elementary particle that holds the key to the understanding of the electroweak symmetry breaking.

So far, the Standard Model is the most successful theory to summarise our knowledge on Particle Physics. The fundamental particles, which are the constituents of our universe, as well as their interactions via the fundamental forces (except for the gravity) are elegantly explained in a concise way. The last building block, predicted by the Standard Model, the Higgs boson, was portrayed as the "Holy Grail" of particle physics, due to the unsuccessful experimental searches for it, going back five decades.

The Large Hadron Collider was designed and built to be able to produce rare processes over a broad energy range, while the detectors at its collision points were built to find, among others, the Higgs boson. With the collaboration of thousands of scientists and researchers across various fields, a significant breakthrough was achieved in the first data taking period of the LHC: a new resonance was found in the searches for the predicted Standard Model Higgs boson.

Precision measurements were employed to measure the mass of the resonance with the least possible uncertainty. The ATLAS and CMS collaborations combined quote a measured mass of

$$m_H = 125.09 \pm 0.21(stat.) \pm 0.11(syst) \text{ GeV} .$$

This thesis focuses on the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel using the data collected with the ATLAS detector during 2012 at 8 TeV center of mass energy. This channel is one of the discovery channels, with quoted observed excess of 6.1 standard deviations over the background only hypothesis and with an expected of 5.8 at the end of the Run-I data taking period. While the statistical significance of the result for the mass searches was enough to announce a discovery of a resonance, additional studies had to be performed to make sure

that the new resonance is indeed the well-sought boson. These studies should focus on the properties of this resonance, such as the couplings of the boson to the other Standard Model particles, as well as its spin and parity properties.

The main point of this thesis is to present the studies on the intrinsic properties of the boson: its spin and its parity quantum numbers. To validate the fact that the observed resonance is the Higgs boson, different scenarios are tested in the data against the SM hypothesis. The possibility of the resonance being a spin-2 graviton has been excluded at more than 99.9% confidence level. Similar is the case for a spin-1 resonance, which has also been excluded at more than 99.9%. Subsequently, assuming that there is no orbital momentum component involved, since the spin-1 and spin-2 models have been excluded, then the quantum number should be spin-0.

Another interesting scenario, which is also experimentally challenging to test, is the determination of the parity quantum number. Now that the spin quantum number is fixed, different hypotheses on the parity quantum number of the Higgs boson give rise to different scenarios beyond the SM. The test performed in this thesis between the positive and negative parity quantum number excludes the CP-odd case. Furthermore, the scenario of a positive parity eigenvalue due to contributions from higher order terms in the Lagrangian due to Beyond the Standard Model physics, is also strongly disfavoured.

Finally, one of the most interesting results presented here is the study of an observed Higgs boson that is an admixture of parity eigenstates, which would be linked to CP violation in the Higgs sector. Various scans have been performed trying to identify such pattern in the collected data, as well as to quantify the possibility of observing such an admixture. The results so far agree with the Standard Model hypothesis within the uncertainties, which are relatively large. So far, only large values of the mixing have been excluded.

To sum up, the Run-I of ATLAS had been successfully completed. An observation of a new resonance in the search of explaining the Electro-Weak symmetry breaking, a problem formalised back in the 1960's, has been achieved. The work presented in this thesis helped in pushing the boundaries of our knowledge and understanding of Particle Physics. The last missing part of the SM puzzle seems to be finally put in its place. With LHC restarting, the Run-II of the ATLAS has officially started. With all the upgrades now in place, we -as the Particle Physics community- should be excited to what the future holds for us.

Samenvatting

Tot nu toe het Standaard Model is de meest succesvolle theorie om onze kennis over deeltjesfysica samen te vatten. De fundamentele deeltjes, wat de bestanddelen van ons universum zijn, evenals hun interacties via de fundamentele krachten (behalve de zwaartekracht) zijn elegant beschreven in een beknopte wijze. De laatste bouwsteen die wordt voorspeld door het Standaard Model, het Higgs boson, werd afgeschilderd als de 'heilige graal' van de deeltjesfysica. Voornamelijk als gevolg van de onsuccesvolle experimentele zoektochten van de afgelopen vijf decennia.

De Large Hadron Collider is ontworpen en gebouwd om zeldzame processen te kunnen produceren over een breed scala van energie, terwijl de detectoren op zijn botsing punten werden gebouwd om, onder andere, het Higgs boson te vinden. Met de medewerking van duizenden wetenschappers en onderzoekers in verschillende velden, werd een belangrijke doorbraak bereikt in de eerste data periode van de LHC: een nieuwe resonantie werd gevonden in de zoektocht voor het voorspelde Standaard Model Higgs boson.

Nauwkeurige metingen werden toegepast om de massa van de resonantie met zo weinig mogelijk onzekerheid meten. De ATLAS en CMS samenwerkingen gecombineerd citeert een gemeten massa van

$$m_H = 125.09 \pm 0,21(stat.) \pm 0,11(syst.) \text{ GeV}.$$

Dit proefschrift richt zich op het $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ verval kanaal met behulp van de verzamelde data gegevens met de ATLAS-detector gedurende 2012 op 8 TeV centrum van de massa energie. Dit is één van de ontdekkings kanalen met geciteerde waargenomen significantie van 6,1 standaarddeviaties boven de alleen achtergrond hypothese met een verwachte significantie van 5,8 aan het eind van de run-I data periode. Terwijl de statistische significantie van

het resultaat van de massa zoektocht genoeg was om een ontdekking van een resonantie aan te kondigen, moesten aanvullende studies worden uitgevoerd om ervoor te zorgen dat de nieuwe resonantie inderdaad het goed gezochte boson is. Deze studies moeten zich richten op de eigenschappen van deze resonantie, zoals de koppelingen van het deeltje tot overige Standaard Model deeltjes, evenals de spin en pariteit eigenschappen.

Het belangrijkste punt van dit proefschrift is om het onderzoek van de meting van de intrinsieke eigenschappen van het boson te presenteren: de spin en de pariteit quantum getallen. Om de waargenomen resonantie is het Higgs valideren, zijn verschillende scenario's getest in de data tegen de SM hypothese. De mogelijkheid van de resonantie als een spin-2 graviton is uitgesloten op meer dan 99,9% betrouwbaarheidsniveau. Hetzelfde is het geval voor een spin-resonantie 1, die ook tevens is uitgesloten op meer dan 99,9%. Vervolgens, aannemend dat er geen impulsmoment component betrokken zijn en aangezien de spin-1 en spin-2 modellen zijn uitgesloten, moet het quantumgetal spin-0 zijn.

Een andere interessante scenario dat ook experimenteel een uitdaging is om te testen, is de bepaling van het pariteit quantumgetal. Nu dat het spin quantumgetal is vastgesteld, geven verschillende hypothesen over het pariteit quantumgetal van het Higgs boson aanleiding tot verschillende scenario's voorbij het SM. De test die wordt uitgevoerd in dit proefschrift tussen de positieve en negatieve pariteit quantumgetallen is exclusief het CP-odd geval. Bovendien is het scenario van een positieve pariteit eigenwaarde als gevolg van bijdragen van de hogere orde termen in de Lagrange voorbij het Standaard Model ook sterk benadeeld.

Ten slotte was een van de meest interessante hier gepresenteerde resultaten het onderzoek van een waargenomen Higgs deeltje met een mengsel van pariteit eigentoestanden, wat wordt gekoppeld aan CP schending in de Higgs sector. Diverse uitgevoerde scans proberen dergelijke modellen te identificeren in de verzamelde gegevens en de mogelijkheid van het waarnemen dergelijk mengsel te kwantificeren. De resultaten tot nu toe komen overeen met de Standaard Model hypothese binnen de onzekerheden, die relatief groot zijn. Tot nu toe zijn alleen grote waarden van het mengen uitgesloten.

Kortom, de Run-I van ATLAS werd met succes afgerond. Een waarneming van een nieuwe resonantie in de zoektocht naar een elektro-Zwakke symmetriebreking, een probleem geformaliseerd in de 1960'er jaren, is bereikt. Het werk in dit proefschrift heeft geholpen om de grenzen van onze kennis en begrip van deeltjesfysica te vergroten. Het laatste ontbrekende deel van de SM puzzel lijkt eindelijk op zijn plaats te zijn gebracht. Met het opnieuw starten van de LHC is Run-II van ATLAS officieel van start gegaan. Met alle upgrades nu op zijn plaats, zijn we -als de Deeltjesfysica gemeenschap- enthousiast over wat de toekomst in petto heeft voor ons.

Μέχρι στιγμής, το Καθιερωμένο Πρότυπο είναι η πιο επιτυχής θεωρία που περιγράφει την γνώση μας στην Σωματιδιακή Φυσική. Τα στοιχειώδη σωματίδια, τα συστατικά δηλαδή του σύμπαντος μας, καθώς κι οι αλληλεπιδράσεις τους διαμέσω των βασικών δυνάμεων (πλην της βαρύτητας) περιγράφονται με μαθηματικά κομψό κι ακριβή τρόπο. Ο τελευταίος δομικός λίθος που προβλέπεται από το Καθιερωμένο Πρότυπο, το μποζόνιο Χιγκς, αποτελούσε το “Ιερό Δισκοπότηρο” της Σωματιδιακής Φυσικής, λόγω των ατελέσφορων πειραματικών ερευνών τις τελευταίες πέντε δεκαετίες.

Ο Μεγάλος Αδρονικός Επιταγχντής(LHC) σχεδιάστηκε και κατασκευάστηκε ώστε να μπορεί να παράγει σπάνιες διαδικασίες σε μεγάλο εύρος ενεργειών, ενώ οι ανιχνευτικές διατάξεις στα σημεία συγκρούσεων του κατασκευάστηκαν για να βρουν, μεταξύ άλλων, το μποζόνιο Χιγκς. Με τη συνεργασία χιλιάδων επιστημόνων κι ερευνητών από διαφορετικούς τομείς εξειδίκευσης, μια σημαντική ανακάλυψη έγινε κατά τη διάρκεια της πρώτης περιόδου λήψης δεδομένων του LHC: ένα νέο σωματίδιο βρέθηκε από τις έρευνες για το προβλεπόμενο σωματίδιο Χιγκς.

Μετρήσεις ακριβείας διεξήχθησαν με σκοπό να μετρήσουν τη μάζα του σωματιδίου με το ελάχιστο δυνατό σφάλμα. Τα πειράματα ATLAS και CMS συνδύασαν τις στατιστικά ανεξάρτητες μετρήσεις τους με αποτέλεσμα να παραθέτουν για την μάζα του μποζονίου την τιμή

$$m_H = 125.09 \pm 0.21(stat.) \pm 0.11(syst) \text{ GeV} .$$

Αυτή η διατριβή εστιάζεται στο κανάλι διάσπασης $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ και στα δεδομένα που συλλέχθηκαν από τον ανιχνευτή ATLAS κατά τη διάρκεια του 2012 όπου ο επιταγχντής λειτουργούσε στα 8 TeV ενέργειας κέντρου μάζας. Το συγκεκριμένο κανάλι παρατήρησε το σωματίδιο και παρέθεσε το στατιστικό

αποτέλεσμα των 6.1 μονάδων τυπικής αποκλίσης, όταν θεωρητικά αναμένονταν 5.8, στο τέλος της πρώτης περιόδου λήψης δεδομένων του ανιχνευτή. Παρά το γεγονός ότι η στατιστική του αποτελέσματος αρκεί για να επιβεβαιώσει την ανακάλυψη ενός νέου σωματιδίου, επιπλέον έρευνες πρέπει να γίνουν για να επιβεβαιωθεί αν όντως αυτό το σωματίδιο είναι το αναζητούμενο μποζόνιο. Αυτές οι έρευνες επικεντρώνονται στη μελέτη των ιδιοτήτων του σωματιδίου, όπως οι συζεύξεις του σωματιδίου με τα υπόλοιπα σωματίδια του Καθιερωμένου Προτύπου, καθώς και τις τιμές της ιδιοστροφορμής και της ομοτιμίας του.

Το κύριο θέμα αυτής της διατριβής είναι η παρουσίαση των ερευνών για τον προσδιορισμό των χβαντικών αριθμών της ιδιοστροφορμής και της ομοτιμίας. Για την επιβεβαίωση ότι το νέο σωματίδιο είναι όντως το μποζόνιο Χίγκς, διαφορετικά θεωρητικά σενάρια ελέγχθηκαν, συγκρίνοντας τα δεδομένα που λήφθηκαν με τις προβλεπόμενες τιμές των χβαντικών αριθμών από το Καθιερωμένο Πρότυπο. Το ενδεχόμενο το νέο σωματίδιο να είναι ένα γκραβιτόνιο με αριθμό ιδιοστροφορμής 2, αποκλείστηκε σε επίπεδο εμπιστοσύνης πάνω από 99.9%. Παρόμοιο αποτέλεσμα είχε κι ο έλεγχος για την τιμή 1, όπου το ενδεχόμενο αποκλείστηκε σε επίπεδο εμπιστοσύνης πάνω από 99.9%. Συνεπώς, αφού αποκλείστηκαν τα μοντέλα με αριθμό ιδιοστροφορμής 1 και 2, ο αριθμός του σωματιδίου πρέπει να είναι 0.

Ένα επίσης ενδιαφέρον σενάριο, αν κι απαιτητικό να ελεγχθεί πειραματικά, είναι ο προσδιορισμός του χβαντικού αριθμού της ομοτιμίας. Τώρα που ο αριθμός της ιδιοστροφορμής είναι δεδομένος, διαφορετικές υποθέσεις για την ομοτιμία του σωματιδίου Χίγκς δημιουργούν ενδιαφέρον για σενάρια φυσικής πέρα από το Καθιερωμένο Πρότυπο. Η έρευνα που παρουσιάζεται στη διατριβή αυτή απέκλεισε το ενδεχόμενο το σωματίδιο να έχει περιττή ομοτιμία. Επιπλέον, το ενδεχόμενο του να έχει άρτια ομοτιμία λόγω συνεισφορών από όρους της Λαγκρατζιανής που αντιστοιχούν σε φυσική πέρα του Καθιερωμένου Προτύπου δεν ευνοείται από τα δεδομένα.

Τέλος, ένα από τα πιο ενδιαφέροντα αποτελέσματα που παρουσιάζονται είναι η έρευνα για το ενδεχόμενο το νεοευρεθέν μποζόνιο Χίγκς έχει για τιμή ομοτιμίας μια μίξη από ιδιοκαταστάσεις του αντίστοιχου τελεστή. Αυτό το ενδεχόμενο θα οδηγούσε σε παράβαση της διατήρησης του αριθμού της ομοτιμίας στον τομέα Χίγκς του Καθιερωμένου Προτύπου. Διαφορετικές έρευνες στα συλλεχθέντα δεδομένα έγιναν για την εύρεση στοιχείων που θα έδειχναν προς αυτή τη κατεύθυνση, καθώς και την προσπάθεια μέτρησης μιας τέτοιας μίξης. Έως τώρα τα δεδομένα συμφωνούν με τις προβλέψεις του Καθιερωμένου Προτύπου, μέσα στα όρια σφάλματος, τα οποία είναι σχετικά μεγάλα. Μέχρι τώρα, μόνο μεγάλες τιμές μίξης έχουν απορριφθεί.

Συνοψίζοντας, η πρώτη περίοδος συλλογής δεδομένων από τον ανιχνευτή ATLAS ήταν πλήρως επιτυχής. Ένα νέο σωματίδιο βρέθηκε στις έρευνες για την κατανόηση του σπασίματος της Ηλεκτρασθενούς συμμετρίας, ένα πρόβλημα που τέθηκε πίσω στο 1960. Η εργασία που παρουσιάζεται σε αυτή τη διατριβή βοήθησε στην ώθηση των ορίων της γνώσης μας για την κατανόηση της Σωματιδιακής Φυσικής. Το τελευταίο κομμάτι του Καθιερωμένου Προτύπου είναι επιτέλους στη θέση του. Με την επαναλειτουργία του LHC, η δεύτερη περίοδος

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MDT PS DCS and LS1 Preparations

A.1 Naming Convention of the MDT Chambers

Every layer is divided in a number of stations. At the barrel region, the numbering of the stations (from 0 to 8) indicate the position of the chamber with respect to the IP in the direction parallel to the beam line. At the end-cap region, the numbering (from 1 to 6) indicates the position of the chamber with respect to the radial coordinate. In addition, along the azimuthal coordinate, the chambers form 16 sectors. The odd-numbered sectors (called *Large*) and the even-numbered ones (called *Small*) have a difference in size by construction, aiming in this way to achieve better azimuthal coverage. Finally, the name of the MDT chamber comes from their relative position in the MS as described above. For example the encrypted name BIL1A12, denotes a chamber in the Barrel region, located at the Innner layer; the station is a Large one, numbered as 1 at the side A and at sector 12.

A.2 Power Supply System of the MDT Sub-Detector

As already described, each MDT chamber consists of tubes that require a high-voltage (HV) supply of 3080V to operate. Furthermore, the readout electronics that perform the actual measurement, as well as the monitoring system mounted on each chamber require a low voltage (LV) of $\sim 5V$

To cover the need of the HV and LV power supplies, the structure of the ATLAS MDT Power Supply (PS) system is structured in a module-based hierarchy. Two Mainframe units (CAEN Mod. SY1527 [157]) located outside, but close to the experimental cavern, are housing 14 Branch Controller units (CAEN Mod. A1676A [158]). The Branch Controller unit, when mounted on a mainframe, has the capability of connecting more than one Easy Crates (CAEN Mod. 3000S [159]) to the mainframe. The Easy Crates are the next entity in the hierarchy of the MDT PS and are organised in groups of five crates in a chain belonging to a single branch controller. The final level of this scheme would be the HV and LV boards housed on each of the Easy Crates. Each crate can accommodate up to 21 single-slot boards, while the first slot of each crate is used for its control. For the power supply needs several types of boards are used depending the specific characteristics on demand in each case (some of the board types are CAEN A3025B [160], A3540P [161], A3016B [162] and differ on voltage (HV or LV), power output, number of channels etc), while in total 68 crates with 339 HV and LV boards (162 for the end-caps and 177 for the barrel) provide the ATLAS MDT PS with 2820 channels. The hierarchy of the system is illustrated in Figure A.1.

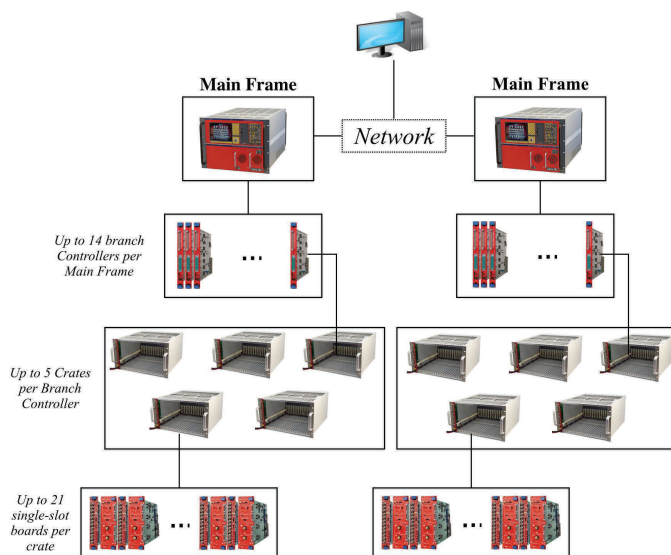


Figure A.1: The hierarchy of the Power Supply system for the MDT chambers.

A.3 Detector Control System of the MDT Sub-Detector

Due to its complexity, the ATLAS detector requires a hardware and software infrastructure to monitor, control and operate all parts of its subsystems. The Detector Control System (DCS) [163, 164] offers the capability to shifters and experts to interact with the detector hardware via a software-based platform.

A coherent and safe operation of the LHC experiments is of utmost importance. An additional aspect that should be addressed is to avoid the duplication of work aiming to reduce the required manpower for development. The Joint Controls Project (JCOP) [165–167] was set up as a collaboration between CERN and the LHC experiments to identify common needs and provide common tools and solutions that the four experiments can use as a basis for the development of their own control systems.

One of the deliverables of JCOP has been the selection of the standard technologies to be used for these systems. These technologies include the standard Supervisory Control And Data Acquisition (SCADA) software package to be used for development of the various needs of each experiment. This SCADA system was selected to be the one developed by ETM named PVSS-II (re-branded as WinCC OA when ETM was absorbed by SIEMENS). Since SCADA systems are in general industrial control systems, one needed additional technology of JCOP was to redefine the operation and control of an experiment as an abstract hierarchical structure, similar to the industrial counterparts. This allowed the implementation of the guidelines for a Finite State Machine (FSM) that was recommended to be adopted by all LHC experiments.

Finally, since all the LHC experiments and LHC itself use similar units (mostly Programmable Logic Controllers (PLC)) to control and monitor the hardware sensors, and JCOP already delivered the standard software packages to be commonly used, the last deliverable was a set of communication protocols and field buses between the sensors and the higher-level software controls. The industrial fieldbus CANbus [168] was suggested and used in most cases. When the hardware devices are connected via ethernet cables the ModBus [169] or the TPC/IP protocols are used. In general, whenever is possible the industrial standard OPC [170] (Object linking and embedding -OLE- for Process Control) is used as the software protocol for communications between the hardware and the software client.

A.3.1 PVSS-II/WinCC OA : The SCADA System

PVSS-II¹ [171] (stands for *Prozess Visualierungs und Steuerungs-System II*) is a software package designed for the field of automation engineering. The main application of the package is to provide the capability of operating and

¹This thesis refers to the SCADA system used by ATLAS as PVSS-II, unless where the migration to the new WinCC OA is described.

supervising a technical installation using workstations with visualisation features. A graphical representation of the role of the software in the automation system is shown in Figure A.2.

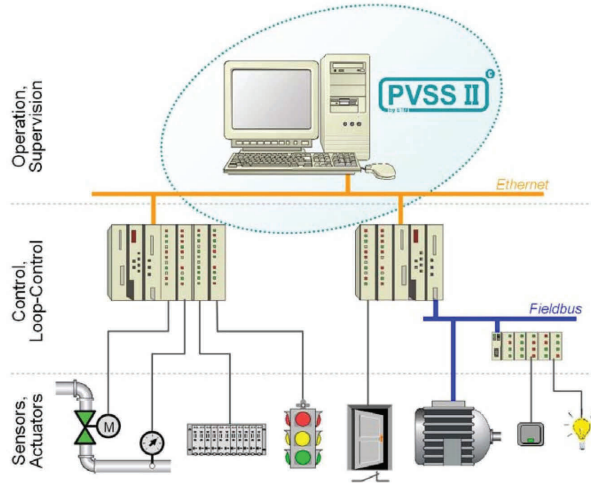


Figure A.2: The supervising role of PVSS-II within an automation control system.

In addition to the visualisation of the process states, the application needs to be able to transfer input values and commands to the process and its control devices. Other functions include alert handling and archiving. The former refers to feature where the system is able to alert the operator when critical states occur, while the latter to the storing of data for later display and analysis. Systems with these features are usually called control systems or visualisation systems, usually referred to by SCADA (Supervisory Control And Data Acquisition) or HMI (Human Machine Interface).

A.3.2 Datapoints

As already mentioned the SCADA system is responsible to provide real-time information on the status of the hardware to the user in the control desk. This information includes every logic state, every "measured value" or "setpoint value" and is represented in the system in the form of datapoints (DPs). A single DP is a structured device-oriented data object containing all the available information. The structured part of the DP is represented via the inclusion of various datapoint elements (DPEs) in a single DP. However, DPEs do not store simply a value, but they also include attributes such as time stamps.

While most of the standard SCADA systems tend to assign a separate datapoint to every variable, PVSS-II takes a modern approach to the issue

in which all available information in the process belongs to logical units of varying complexity, called "device".

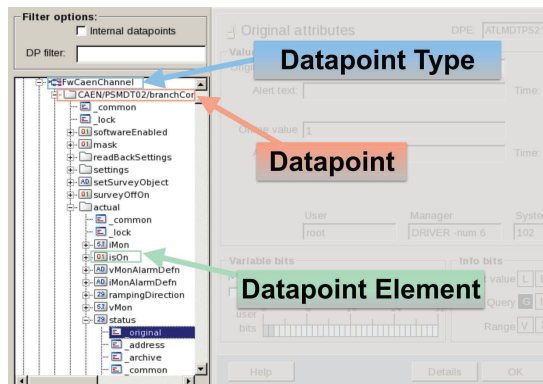


Figure A.3: An example of the datapoint structures. Specifically the DP of the high voltage channels is depicted. The DPEs structure below is also shown.

An example of datapoints and datapoint elements are shown in Figure A.3. The datapoint of type "FwCaenChannel" (the "device" here is a channel) includes all information for the channels of a circuit board made by CAEN that is used to provide high voltage output to a MDT chamber. The values and states are internally organised in logical groups (readBackSettings, settings, actual, etc).

A.3.3 The ATLAS DCS Architecture

Detectors such as ATLAS need a well designed and organised back-end architecture for their monitoring and control needs. In general terms, ATLAS is mainly operated by two collaborating systems: the DCS and the Trigger and Data-Aquisition (TDAQ) system.

The DCS system is responsible for the supervision and control of the hardware of the experiment as well as its infrastructure. On the other side, the TDAQ system is responsible for reading out the detector and directing the data streams from the digitisers to the mass storage units (see more in Section 2.2.5). The TDAQ operates only during physics data taking periods while the DCS system is responsible for continuous monitoring and control of the detector equipment and is supervised by a human operator in the control room.

The ATLAS DCS system is categorised in four abstract groups:

- **LHC Overview:** information about the accelerating complex and information provided by other experiments of LHC
- **Systems:** all systems required for the data acquisition (DAQ, Data

Quality) and all sub-detectors (Inner Detector, Calorimetry and Muon Spectrometer)

- **Services:** common services used for the technical operation of the detector (cooling, gas systems, cryogenics, electrical network)
- **Infrastructure:** safety system, radiation monitoring, magnets, counting rooms, cavern, environmental information, computer and network and database servers

A.3.4 Datapoints for the MDT DCS PS System

The hierarchy of the hardware units of the PS of the MDTs is used to define the datapoints of the DCS. Since PVSS-II can structure the information (DPEs) into devices, the datapoints of the software are structured to follow the hardware hierarchy. Therefore the datapoints corresponding to the chambers are used. Each chamber has a LV and HV power supply which are provided by specific channels of a HV/LV board, which in turn is included in an Easy Crate. The specific Easy Crate is mounted via a single branch controller unit to a mainframe. This structure defines a coordinate-like format which matches each datapoint to a specific position in the connection chain.

The datapoints contain all the necessary information to assess the full status of the chamber. The mapping information is stored in each datapoint for all three channels of the chamber: LV channel for the electronics and HV channels (two in most cases) for the first and second multilayer. There is additional information, grouped for every channel, concerning the PS channel trip handling and flags.

The trip handling node includes elements concerning the trip limit change during ramping (`tripLimit`, `tripLimitDuringRampUp` and `rampingUp` elements) and the trip recovery. The trip limit (`i0`) of every HV channel needs to be higher than the nominal one during the ramping phase, but it returns to the nominal value after the ramping has finished. The trip recovery process makes use of the rest of the elements in the `tripHdl` node. In the case where a channel trips, the `TRIPPING` element becomes `TRUE` while the `tripCounter` increments by one. Then, if the `tripRecovery` is set, the channel will be automatically reset and ramped up. If this tripping behaviour continues and the `tripCounter` reaches the `tripCounterLimit` value then, the `tripRecovery` element will be set to `FALSE` and the channel will not be switched on again, requiring intervention by the experts (manual dropped recovery).

The flags provide crucial information about the channel status and are used to define possible errors and to ensure the safe usage of the channels (whether a channel can be turned on or not). All of the channels contain a temperature information flag (`tempInterlock`) which is raised when the temperature of the PS module in which the channel of the chamber belongs, exceeds a certain pre-defined value. Specific to HV channels is the `gasInterlock` flag, which is raised

automatically in case of a problem with the gas distribution on the chamber. Instead of the `gasInterlock` flag, the LV channels have the `eltxInterlock` flag, which indicates problems with the electronics of the chamber. Finally, for all channels there is the `disabled` flag. This flag is raised manually by the experts in case there is any other problem with the channels and it must be prevented from being turned on. The most common example for these flags, is when a channel is constantly tripping and is in need of further investigation by the experts of the system. In this case the expert can raise the disable flag, which makes the channel immune to the propagation of commands to it.

In addition, since the datapoints in PVSS-II represent complex logical units, they have an internal organisation. Each datapoint has the elements grouped in three main categories:

- **actual:** The group contains the current (**online**) values of the channels. Voltage (`vMon`), current (`iMon`) and power state of the channel (`onOff`) are in this group.
- **settings:** The group contains the set-up values which are used for proper operation. Voltage (`v0`), trip limit current (`i0`) and ramp up and down steps (`rUp`, `rDwn`) are in this group.
- **readBackSettings:** This group contains the values the hardware has internally stored and using that specific moment.

Apart from the online values each datapoint also contains a number of configurations (**configs**). They provide additional functionalities to the datapoint elements. The most important of them are described below:

- **Alerts:** For each of the monitored parameters, PVSS-II provides a built-in alarm mechanism which notifies the end-user if the value of a parameter moves into a non-nominal range. The predefined limits around the nominal value for each datapoint are stored in the `_alert_hdl` configuration as well as the ranges around the nominal value that define the severity of the alarm. A developer can set three alert severity levels by setting three continuous and mutually exclusive ranges above and below the nominal value. These should correspond to a **WARNING**, an **ERROR**, or a **FATAL** state. In addition, there is the possibility of setting an alert to require acknowledgement by the user or the expert of the system, as well as of hiding intentionally (*masking*) known alarms. The masking procedure is followed by the expert to hide certain known alarms to prevent them from appearing in the user interface that displays the alarms: The Alarm Screen.
- **Archive:** The archive configuration is crucial for both the developer of the system and the end-user. This configuration sets up an efficient monitoring tool by providing a log functionality and the capability to trace back and keep in archive the values of the datapoints and alerts.

The history of all values is stored in either the RAIMA [172] or the Oracle [173] database, thus providing the capability to determine the status of the channel during debugging or simply used for the physics data reconstruction procedure. In both cases, the `_archive` configuration accommodates all the necessary information about the archiving.

- **Function:** In hardware terms, a PS Board uses a collection of EPROM (Erasable Programmable Read Only Memory) registers to store the output values as well as certain conditions (power, environmental, etc) under which the board operates. These registers are simply a collection of bit-structured information that the control software reads. A typical way to reduce the amount of transmitted data from the board to the control software is by packing relative information bits in a single register. In this case however, there is a single register that also includes information for various parameters of the board. For example, the status of a channel is a 16-bit word that contains the full information about the state of the channel as well as all the boolean errors that may occur. Information such as whether the channel is switched on or off (bit-0), the ramp-up and -down steps (bit-1 and bit-2), whether a channel is unplugged (bit-11) or even whether the channel has raised an **OverVoltage** (bit-4), a **Power Fail** (bit-14) or a **Temperature Error** (bit-15) are all grouped in the status register. To handle this compact information, as well as to combine information from other datapoints that also have this compact information, the function configuration is used. The configuration `_dp_fct` contains all the user-defined automated responses built from a pool of mathematical, logical or statistical functions. The response from a certain datapoint will be triggered when the value of the datapoint changes and it can simply be a new value on another predefined datapoint or a signal event, which may trigger another action.

A.3.5 The Finite State Machine

The ATLAS DCS Finite State Machine (FSM) [174] delivered with the JCOP framework uses the State Management Interface (SMI++), which has been initially developed for the Delphi experiment and provides the tool to build a FSM and an Expert System which is vital for controlling large experiments.

The FSM toolkit allows to model the hierarchical organisation of the control system and to sequence the operation of the detector according to a well-defined set of states and possible transitions. The FSM toolkit allows for the design and implementation of dedicated state machines of the detector systems and of software procedures. The collection of these device-oriented state machines can be strictly organised in nodes of higher-level state machines, following a parent-children relationship. The parent node derives its state by the states of the children nodes below via a programmable logic, while in the same time a command that will be addressed to a parent node propagates to

all the children nodes below, allowing for the full detector control system to be supervised by a single state machine unit. Each node can be found in a specific set of states and can have a specific set of commands.

As described above, in the hierarchy of the FSM tree, the information about any node propagates from the children to the parent node. This is also the case for two important instances : State and Status. The State defines the operational mode of the system. For example, if a chamber is in operation with all its channels on, the state is "ON", while in case that everything is off, the state is "OFF". On the other hand, the status describes how well the node is operating in the current state. For instance, if one of the channels of the chamber has an error, the node that corresponds to the chamber will be in status of "WARNING", "ERROR" or "FATAL" depending on the severity of the error.

A.4 Preparation of MDT DCS for Run-II and LS1 Tests

A.4.1 Inclusion of the End-cap Extension Chambers

The end-cap Extension Chambers (EE chambers) are MDT chambers that are part of the ATLAS Muon Spectrometer. During the first installation of ATLAS these chambers were not included in the end-cap part of the detector. However, it was decided that these chambers should be included as a means of providing an extra point of measurement which is needed to calculate the sagitta of a muon track.

The chambers are located in the pseudorapidity range of $1.1 - 1.4$ and encircle the end-cap toroid magnets (Figure A.4). The inclusion of these chambers in the ATLAS MS aims for an improved efficiency in the aforementioned pseudorapidity range (Figure A.4).

For the EE chambers, the first end-cap side (side C) was included in the ATLAS installation during the winter shutdown of 2011-2012, while the other side (side A) was commissioned in the Long Shutdown-1 (LS1) during the winter 2012-2013. During the installation of these chambers, the ATLAS DCS support, as well as the development of new panels for the new chambers, was also vital.

The PS system has to supply the new chambers and therefore the installation of new HV and LV boards was needed. For example, for the EE chambers in side A, two additional HV boards were necessary and they were added (HV boards 12-0-9 and 12-0-11) during the shutdown. For each new piece of hardware added in the system, a validation of the existence of all the necessary information for the control system is required. Therefore, the mapping, the addresses etc. were all checked and enabled for all the new channels.

In addition to the hardware upgrades, new FSM panels had to be developed or updated in order to support control and the monitoring of the new chambers.

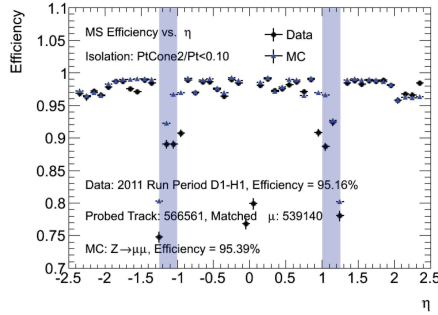
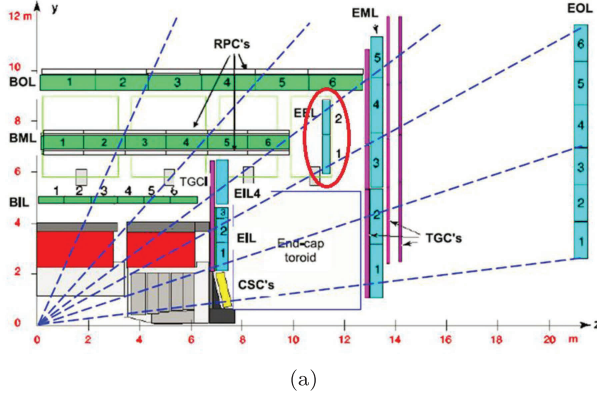


Figure A.4: Location of the EE chambers in the ATLAS Muon Spectrometer (a) and efficiency as a function of pseudorapidity for the ATLAS Muon Spectrometer (b). The region where the EE chambers are inserted is highlighted.

Summary-, chamber- and partition- level FSM panels have been developed for both the Power Supply and JTAG systems. Figure A.5 gives an example of these panels, where the Summary panel for the Power Supply System of the MDT chambers in endcap side-A is shown, updated to include the newly installed chambers.

A.4.2 Board-Test Project

The Power Supply system of the ATLAS detector uses a large amount of HV and LV boards. As expected with such amount of boards malfunctions do occur. The CAEN Board Testing Project is an independent PVSS-II project dedicated to perform benchmark crash-tests to the PS-related hardware equipment which malfunctioned and was replaced during operation. The whole project

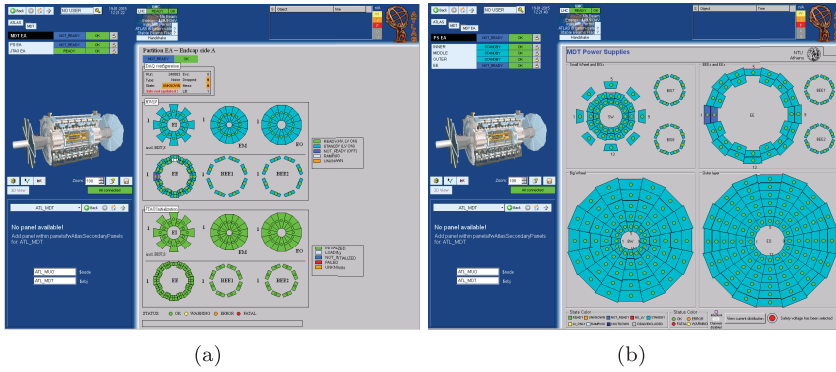


Figure A.5: (a) A snapshot of the FSM Main Panel corresponding to the end-cap side A of the PS system of the MDT part of the ATLAS MS. The newly commissioned EE chambers are shown. One level below, the PS of the end-cap side A is shown at partition level (b).

is a miniature of the ATLAS Power Supply scheme featuring a Mainframe on which a Branch Controller is mounted to connect a CAEN EasyCrate. On the crate a variety of HV and LV boards are mounted in order to be tested. Table A.1 summarises the modules that are tested by this project.

Module ID	Module Type	Information
A3009	LV Board	12 channels, 8V, 9A, 45W
A3016	LV Board	6 channels, 8V, 90W
A3025	LV Board	4 channels, 8V, 25A, 150W
A3540	HV Board	12 channels, 4000V, 1mA
A3512	HV Board	6 channels, 12000V, 1mA
A3802, A3802	ADC/DAC Units	128 channels
A3485, A3486	3-Phase 220/400 Vac.48Vdc Converter	2 channels, 2 (2.5)kW
EASY3000S	EasyCrate	10 board slots, up to 2kGauss
SY1527	Mainframe	16 board slots, 3400W

Table A.1: List of the equipment used by most of the ATLAS muon sub-systems and tested by the Board Testing Project.

The user interface of the project is shown in Figure A.6. It consists of a single window split in half to represent the two crates that are available. At any moment, the end-user can add or remove boards from the crates. PVSS-II is aware of the mechanical and electronic characteristics of the board via the fwCaen JCOP Framework Component [175]. For example, if a user adds a CAEN A3009 [176] LV Board module in slot 0 of the crate, the software handles the fact that the board is a 4-slots one and consists of 12 channels and can read

the information provided by the registers of the board into specific datapoints. For each device under test, the end user should set a specific numerical ID for the board that would act as a tag for the output file and also has the capability of adding specific comments via the "submit comments" button.

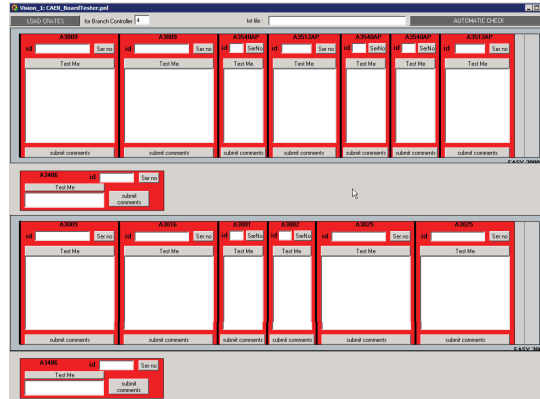


Figure A.6: The graphical user interface of the Board Testing project.

By pressing the "Test Me" button on each board instance on the user interface, the project performs a full benchmark test that lasts about twenty hours. This test consists of three full cycles, which in turn consist of four phases:

- 2 hours switching ON/OFF, with 300s interval;
- 1 hour steadily ON;
- 2 hours switching V_{min}/V_{max} , with 300s interval;
- 1 hour steadily ON;

The output of each test is stored in a text file and consists of three parts

- Header:
The header of the output file includes some generic information about the date and time of the test, the board ID the user has set for the test and the model of CAEN board module.
- Main Body:
The main body of the output file is a simple table in which the first column is time in seconds, followed by the voltage and current values per channel of the board as well as a string of status bits representing possible error flags. The table is filled per row when a value in one of the voltage, current or status columns changes.

- Footer:

The footer of the output file has the summary of the test. The summary consists of the time that test had ended, the total duration of the test, the temperature of the board. Finally, summing up the status bits, the project summarises by channel the occurrences of all the possible errors that the project checks for. The possible errors that can occur during the board test are:

- Temperature Error;
- Power Failure;
- Unplugged;
- Calibration Error;
- Internal Trip;
- Over HVMax;
- Under Voltage;
- Over Voltage;
- Over Current.

At the end, the user can collect the data from all the crash-tests and compile a report on the amount of equipment failed per type as well as which is the most common types of error each equipment type presents. For the period of 1st November 2011 to 30th April 2013, the information is presented in Table A.2 and summarised in Figure A.7.

Module Type	Available	Installed	Sent for maintenance	Percentage (%)
A3009	86	78	1	1.3
A3016B	31	28	0	0
A3025B	233	217	2	0.9
A3540AP	208	192	18	9.4
A3512AP	57	49	1	2.0
A3801	54	48	3	6.2
A3802	28	24	1	4.2
A3486	27	24	1	4.2
A3485	29	24	1	4.2
EASY3000S	68	64	0	0
EASY3000	98	92	0	0
A1676A	38	32	0	0
SY1527	8	6	0	0
Total	965	878	29	3.3

Table A.2: Type of modules and number of boards per type that was sent for maintenance after proved malfunctioning under the Board Testing crash-tests.

For the MDT muon subsystem, statistics show that the HV board A3540AP has the most malfunction occurrences, which can be expected since it is the

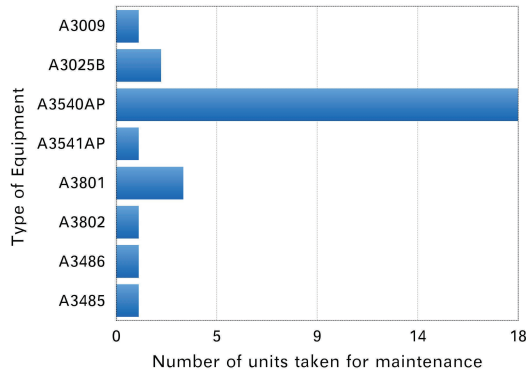


Figure A.7: Types of boards taken for maintenance from the cavern during the period 1st November 2011 to 30th April 2013.

most commonly used type of HV supply board. One can define the type of error that is most frequently presented for the channels of this type of board. This information is shown in Figure A.8, where is apparent that almost 66% of the A3540AP HV boards that malfunctioned had raised the Under Voltage error flag during the Board Test. Such information provides useful feedback both to the maintenance personnel, as well as to the system experts, since for example, if a specific type of error is repeated for the same board over a period of time, this behaviour needs additional investigation and could possible hint to more general issues (firmware, hardware condition, etc.).

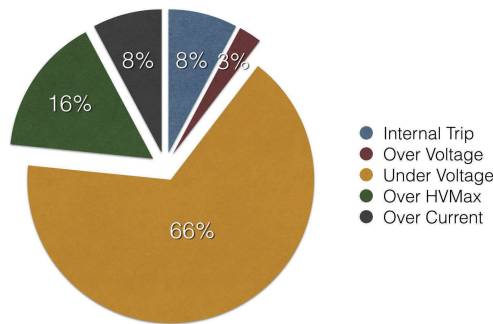


Figure A.8: The type of error flag HV Boards A3540AP most frequently present during the benchmark tests.

Finally, the user can also produce statistics about how often the Board Test fails to reproduce the exact malfunction of a board that occurred during operation. In general, the fact that a board malfunctioned during operation

does not imply that the board will always malfunction in the future. Therefore, if an actual problem exists the Board Test should be able to reproduce a problem with the specific board. One can define four categories to produce such statistical study:

- Irreproducible : The board during the crash-test performed well with no errors.
- Multiple Errors : The board during the crash-test produced multiple error of various types.
- Temporarily Irreproducible: The board has been tested multiple times in short period of time and in some tests presented errors, while in others performed well.
- Unlucky : The board has been tested and no errors occurred during the crash-tests, but was then put back in the detector and after long period of time, it malfunctioned and was tested again. This behaviour was repeated more than once.

As it is depicted on Figure A.9 the most common issue is that a board malfunctioned during operation but an error is irreproducible during the crash test where the board performed well, with a percentage value of 36.3%. Additionally, it is unfortunate to see a percentage of 27.3% in the "Unlucky" category. This represents a number of boards that malfunctioned during operation, removed and tested with the Board Test Project, where they performed well so they were returned in the cage with the spares, but when the specific board was reinstalled in the PS chain and set to operation, it malfunctioned at some point and was removed and tested again.

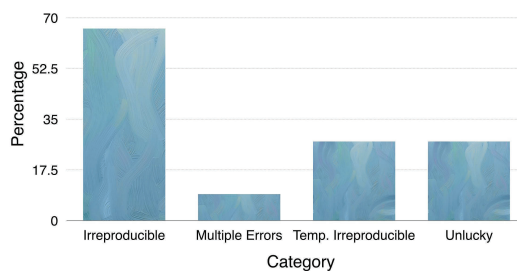


Figure A.9: Bar plot of statistics for percentage different types of irreproducible errors on HV boards by the Board Test Project.

Using this information, the experts and the technicians gain knowledge of the issues and can focus on reproducing the conditions a board is under during operation more precisely. This results in better understanding of the

real-life operation cycles of the board, so more precise tests can be designed and developed for the Board Test Project. One example of this procedure is the following: during operation some channels of a board can momentarily be over current due to sparks in between them. In general, during operation this behaviour is normal. However, during the crash test, adjacent channels seemed to create sparks and the test was resulting in over current errors. These errors had to be avoided, since the performance of the board is evaluated from the performance of the independent channels. To fix this, the cycles of the test where the channels of the board were all switched on to the maximum voltage at once was split in two subsequent cycles. The newly developed cycles now are switching on and off only the even-numbered channels during the first cycle, while the odd-numbered channels remain switched off constantly. Then, during the second cycle the odd-numbered channels are switched on and off, while the even-numbered channels are constantly switched off. This development successfully alleviated the sparks issue during the crash tests.

A.4.2.1 Preparation for Run-II: Migration of PS Systems to WinCC OA

During the LS1 of the ATLAS detector, the SCADA version of the control system was upgraded from the ETM PVSS-II version to Siemens WinCC OA, since support and development of the old framework had stopped. This fact implied that all the production and development machines had to be upgraded to the latest software package version for the SCADA system as well as the OPC-related software.

The Board Test Project, described in the previous paragraph, having the advantage of being independent of the operation of ATLAS was a perfect candidate to be the first to be upgraded, as it was not interfering with the monitoring of the upgrade procedures of the ATLAS PS system. After identifying all the changes of the frameworks, all datapoint types and datapoints were successfully migrated to the new software version. Several communication issues related to the new OPC server version have been addressed and the project was back on-line and running under the new environment.

The experience gained from the migration of this independent project was used shortly after to migrate the production machines (namely PS2 and PS3) that are used to control the Power Supply System for the barrel and end-cap MDT and CSC chambers of the ATLAS Muon Spectrometer.

For the projects under the new environment, to verify that all the information is in place, a validation tool was developed (Figure A.10) as an Experts Tool. This allowed for an automated way to check the existence and validity of the migrated datapoints that are necessary for the smooth operation of the system.

The top part of the validation tool takes into account the selection of the channels that should be checked. The end user can select if the wanted selection should be restricted to either the barrel or end-cap channels, or not restricted

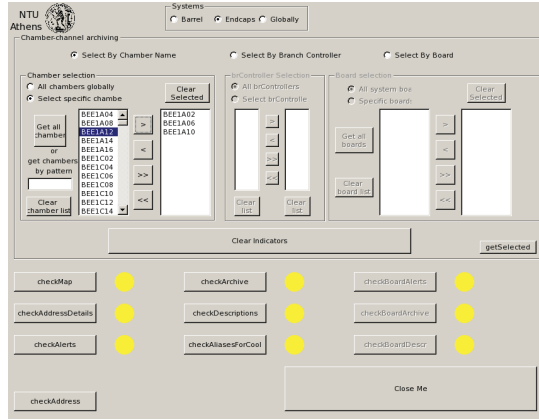


Figure A.10: A snapshot of the validation panel developed to verify the existence of the various information necessary for the smooth operation of the ATLAS MDT PS.

and all the channels should globally be checked. Then below there is the actual selection separated into three possible categories. The user can either select the channels by chamber name, by the branch controller ID that all the channels are children of, or by the board ID that contains the channels as children. When the selection is made there is a variety of buttons in the bottom part of the panel that checks the following information:

- Map (chamber only) : If the information about the channels (HV and LV) that supply the chamber exists.
- Address details : If the information about the address details are correct and enabled. This enables the communication and the readout of the values.
- Alerts: If the alert configuration exists, if it is correct and enabled.
- Archive: If the archive configuration exist, are correct and enabled.
- Descriptions: If the information on the alarm description exists and is enabled. This corresponds to the information that is displayed in the Alarm Screen when an alarm appears.
- Aliases: If the unique aliases for the elements exist. This is used via the database communication.

A.4.3 Summary of Run-II Preparations

With the efforts of the technicians, experts on-call and shifters, the ATLAS Muon Spectrometer and its Control System had successfully completed the

ATLAS Run-I with an overall efficiency of about 99.7%, concerning uptime. During LS1, new chambers, electronics and framework environments were installed, requiring for further development on the DCS side. The success of these developments was validated during the ATLAS test run weeks, which showed that the system is fully operational and ready for a successful Run-II.

APPENDIX B

Geant4 Simulation of the Micromegas Detector

This chapter introduces the technology of the resistive micromegas² detector, in an effort to simulate the detector response using the Geant4 [139] framework. The technology is chosen for the Phase-II upgrade of the ATLAS Muon Spectrometer [177]. Specifically, the micromegas (together with TGCs) is scheduled to replace the MDT and CSC technologies of the ATLAS Small Wheel, that is the endcap region right after the end of the barrel. In this part of the ATLAS detector, the micromegas should be able to withstand a radiation harsh environment, mainly consisting of photons and neutrons. The motivation behind the simulation presented here is to understand the detector response in such an environment.

B.1 The MicroMeGaS Detector

The micromegas detector [178,179] introduced by I. Giomataris and G. Charpak is a gaseous detector designed to have high granularity, as well as good momentum and time resolution.

A drawing of a micromegas detector is shown in Figure B.1a. The gas-filled chamber is split into two main regions: the *drift gap*, which is the region between the drift electrode and the woven wire mesh with a size of few millimetres; and the *amplification gap*, which is the region of about hundred micrometers between the mesh and the readout plane. The gas is usually chosen to be a mixture of a noble and a poly-atomic gas. The readout plane consists of parallel copper strips on a Printed Circuit Board (PCB), while the

²The naming is the abbreviation of the phrase *Micro-MESh Gaseous Structure*.

micro-mesh is held in position by cylindrical non-conductive spacers, referred to as *pillars*. By applying high voltage, the two regions develop an electric field with different magnitude per region.

When a charged particle crosses the detector, if it is energetic enough, it ionises the atoms of the gas creating ion-electron pairs in the drift gap. Due to the electric field, the electrons from the ionisation (primary electrons) drift towards the mesh, while ions towards the drift plane. By keeping the anode strips grounded and the size of the amplification region relatively smaller than the drift one, the electric field in the amplification gap is about a hundred times stronger than the one in the drift gap. This high electric field allows the electron to gain energy and to be capable of producing further ionisations, creating an avalanche [180,181]. This multiplied electron avalanche is collected by the anode strips and readout via the front-end electronics of the detector as the final signal.

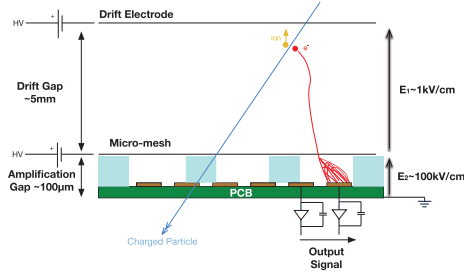
The technology of bulk micromegas detector is being studied by the Muon ATLAS MicroMeGaS Activity (MAMMA) as a potential candidate for the upgrade of the Small Wheel ATLAS Muon Spectrometer. The requirements for the upgrade are for a technology that is able to provide fast tracking inputs to the Trigger System. To withstand the radiation hard environment of the ATLAS Small Wheel, new prototypes have been developed. The resistive chamber prototypes were studied since 2009. The most prominent design proved to be the addition of a layer of graphite enriched *resistive strips* with resistivity of a few $\text{M}\Omega/\square$ [182], as shown in Figure B.1b. The choice of strips instead of a single resistive layer proved to reduce the charge spread across several readout strips, while at the same time if a discharge arises, the area affected by it is kept as small as possible. This innovation allows for the detector to maintain its high rate capability, being able to identify minimum ionising particles with excellent precision in a radiation hard environment.

B.2 MicroMeGaS Simulation

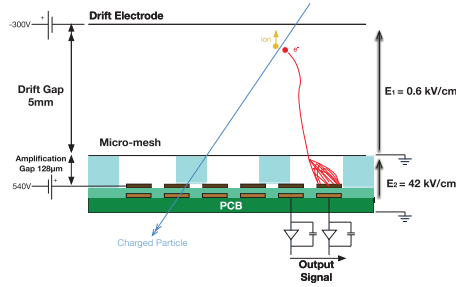
The Geant4 framework provides a well-validated environment to simulate the interaction of particles with matter. Deriving classes from the package, the end-user can define the geometry and the physics in which he/she is interested to perform the simulation. In this chapter, a simulation of a micromegas detector prototype is performed. The end-goal is to identify the energy deposited in the active area of the detector, when the module is placed in front of a hadron or photon source. Low-energy electromagnetic physics is simulated by Geant4 and is compared to data collected by test-beams for the purpose of validating the simulation.

Each Geant4 application consists of at least four basic user-defined classes. These are commonly referred to as

- Detector Construction: defines the materials, the geometry and the sensitive (interesting simulation-wise) parts of the detectors under study;



(a)



(b)

Figure B.1: (a) A schematic of the initial configuration of the micromegas detector. The planes of the drift electrode, the micro-mesh and the readout plane define the drift gap, and amplification gap regions respectively. The micro-mesh is held in place by non-conductive pillars. The high voltage is applied to the drift electrode and to the micro-mesh generate the electric field per region. A charged particle ionises the gas and the electron drifts towards the micro-mesh. Then the increased electric field forces the primary electron to generate an avalanche which is finally collected by the readout strips. (b) A schematic of the modified configuration of the micromegas detector with the addition of a layer with resistive strips above the readout ones. The charge collected on the resistive strips is induced to the readout strips and then readout as the detector signal.

- **Physics:** defines which particles are to be used in the simulation, as well as the physics processes that can be simulated;
- **Primary Generator:** defines the source of the primary particles. This can be a particle gun, a beam coming from an accelerator, or any generalised

source. The geometry of the source, and the properties of the generated particles are defined in this class;

- Run and Event Actions: define what actions the simulation should perform during the beginning and the end of each run and of each event.

On the following, a short description of the above structures is presented as a quick overview of the application.

B.2.1 Detector Construction

As already mentioned, the micromegas chamber is planned to be installed in the ATLAS cavern during the ATLAS Long Shutdown 2 and is meant to be an upgrade of the Small Wheel. While large-area chambers are being constructed and tested for the purposes of the upgrade, the working principles are derived from the smaller prototypes that have been (and are still being) tested over the past years. Therefore, for the purposes of the simulation a small-area resistive bulk micromegas detector is tested. The software developed is easily extendible and similar simulations can be performed for large-area chambers too.

The detector is placed in the volume of the experimental area, referred to as *World* volume, which is filled with air. In detail, the chamber (Figure B.2a) consists of a PCB 20 cm $\times$ 20 cm made from G10 material. On it, a layer of copper readout strips cover the 10 cm $\times$ 10 cm active area of the detector. The strips are 17 μ m thick with a strip pitch of 250 μ m. The layer of the readout strips closer to the PCB is usually referred to as the X plane readout, since it is set to readout the horizontal dimension of the chamber geometry. The readout strips are within a layer of epoxy¹ (glue) 25 μ m thick. An insulator layer made of kapton, 25 μ m thick, is placed on top of the epoxy layer. The same structure is repeated for the next readout plane; on top of the kapton layer, the Y (vertical) readout strips are placed. The Y readout layer is of the same geometry as the X layer but only rotated by an angle of 90° with respect to the center of the detector. Similarly to the previous formation, the Y readout layer is within a 25 μ m thick layer of epoxy, followed by a 25 μ m thick layer of kapton. Finally, on top of the last kapton layer, the layer of the resistive strips is placed. The resistive strips are only placed in one direction and they have the same geometry as the readout strips, but are made from a high resistivity commercial material consisting of a graphite and epoxy mixture². This layered profile is shown in Figure B.2b.

The next region of the detector, above the resistive strips is filled with the gas mixture and is the amplification region of the detector. For this type of detectors the amplification gap is 128 μ m. At the end of this gas volume the mesh wires made of woven Stainless Steel covers the active area of the detector

¹Epoxy is C₃H₅OCl

²Nanometric carbon in epoxy resin type RS 12000 by ESL

(Figure B.2c). The mesh wires have a radius of $12\mu\text{m}$ with a pitch of $78\mu\text{m}$ and the whole layer is supported by insulating cylindrical pillars of $200\mu\text{m}$ in radius. Above the mesh, the second gas volume defines the drift gap, which starts above the mesh layer and extends up to the drift anode. The drift gap in these prototypes is 5mm. The drift electrode is identical to the mesh. The amplification and drift gap is split into two logical volumes. This would allow the end-user to apply an electric or magnetic field, if tracking studies are needed.

The total height of the detector is 2 cm. The total gas volume is closed on the sides with an aluminium frame of 3 cm in thickness, while above the frame the gas volume is enclosed by a layer of mylar (of $120\mu\text{m}$ in thickness) followed by a layer of PCB covered with a layer made from brass. The two last layers have both a square hole of the size of the active area in their center. The materials used in the simulation for building the different parts of the detector are summarised in Table B.1.

All parts of the detector are taken as sensitive detector regions. The term sensitive detector in the Geant4 terminology describes the regions in space in which when a transversing particle changes direction or loses energy the information about this change is stored.

Part	Material	Composition
PCB	G10	8.16%Na, 35.53%O, 2.29%Ca, 0.37%Al, 22.16%Si, 1.57%Mg, 13.66%C, 1.91%H, 13.45%Cl
Readout Strips	Cu	100%Cu
Insulators	Kapton	69.11%C, 2.64%H, 7.33%N, 20.92%O
Resistive Strips	C in Epoxy	52.02%C, 4.28%H, 13.59%O, 30.11%Cl
Glue	Epoxy	38.92%C, 5.45%H, 17.30%O, 38.33%Cl
Mesh, Drift	Stainless Steel	74.62%Fe, 16.90%Cr, 8.48%Ni
Frame	Aluminium	100%Al
Window	Mylar	62.50%C, 4.20%H, 33.30%O
Brass Cover	Brass	70%Cu, 30%Zn
Ar : CO ₂ Gas	Ar : CO ₂	93%Ar, 7%CO ₂ (~ 1, 91%C, 5.09%O)
Air	Air	0.01%C, 75.53%N, 23.18%O, 1.28%Ar

Table B.1: A summary table of the different parts of the detector and their material composition in terms of chemical elements.

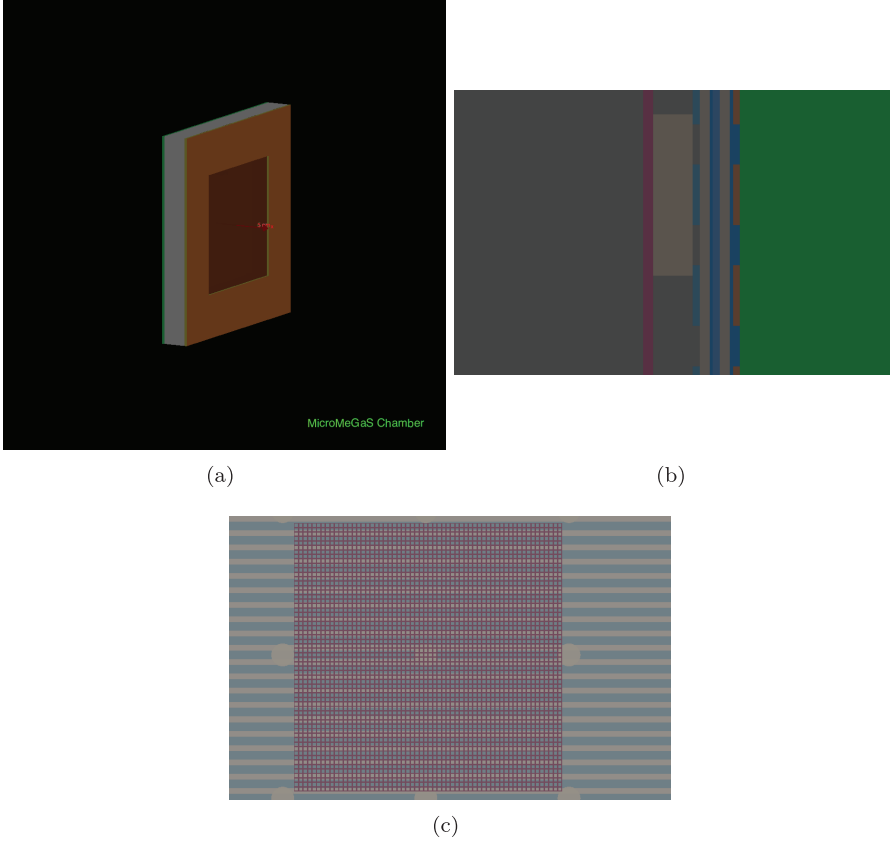


Figure B.2: (a) The micromegas detector within the World volume filled with Air. The center of the PCB (green) of the detector is the $(0, 0, 0)$ point of the World. The X dimension is defined as orthogonal to the surface of the chamber. The Y dimension is the vertical from the center pointing upwards, while the Z is the horizontal pointing inwards. (b) A zoom in view of the layers of the readout plane of the detector. The green part is the PCB, on top of which the first readout strip (brown) layer is immersed in epoxy (blue). On top, a layer of kapton (light brown) is followed by another layer of readout strips with their direction rotated by 90° with respect to the previous ones. Another layer of kapton is followed by a layer of resistive strips (dark green). Finally the pillars (light brown) are placed between the resistive strips and mesh (red). (c) A view from above of the interior of the detector. The mesh is shown, placed on top of the light brown cylindrical pillars.

B.2.2 Physics Lists

The most basic physics process in the simulation is the transportation of a particle between two space points. In Geant4 the transportation within a volume is performed in steps. The particle transportation is the process that determines the limits of the step that will take place inside a geometrical volume. The length of the step with which a track will proceed into another volume is calculated by this process. In addition, when the track reaches a boundary region, the process identifies the next volume that the particle track will enter. The length of the step is calculated by sampling the mean free path distribution:

$$\lambda(\epsilon) = \left(\sum_i [n_i \cdot \sigma(Z_i, \epsilon)] \right)^{-1}, \quad (\text{B.1})$$

where ϵ denotes the energy of the incoming charged particle, while the sum, $\sum_i$, runs over the different components of the gas mixture. The $n_i = N_A \rho / A$ is the number of atoms per volume, N_A is the Avogadro's number ($6.022 \cdot 10^{23} \text{ mol}^{-1}$), ρ_i the density of the medium and A the atomic mass. The mean free path also depends on the total cross section per atom of the process, $\sigma(Z_i, \epsilon)$.

During the course of its trajectory the particle can interact with the surrounding material. For a single physics process, Geant4 calculates, per step of the trajectory of the particle, the cross section of the process. In case the process occurs, then at the end of the step, Geant4 implements the results of the physics process on the characteristics of the particle (i.e. momentum magnitude and direction, position, energy of particle etc.). Pre-defined sets (*lists*) of such processes are defined by the Geant Collaboration, each tuned for a set of applications. In this chapter, simulations with two different primary particle types, photons and hadrons, are described.

In the case of photons, the software needs to be able to successfully describe the deposition of energy within the micromegas detector, when the primary particles arise from radioactive sources. The use of such sources (e.g. ^{55}Fe and ^{109}Cd) is common as their spectrum is well known and can be used for calibration purposes. The recommended physics lists [183], given by the Geant4 collaboration, include all the necessary interactions for a specific application (i.e. dosimetric, High Energy Physics, or Medical applications). For the software presented here, the low-energy (*emlowenergy*) photons physics list is implemented. The list is based on the broader Livermore physics list [184] and includes all the cross-sections for photoelectric, Compton scattering, Gamma Conversion, Ionisation, Multiple Scattering (Wentzel Model [185]) and Bremsstrahlung processes at the *keV* energy range. In addition to this list, the decay process is manually included.

Similarly, in the case of hadrons, the software needs to provide information on the energy deposition in the case of neutron and pion beams. Since the number of possible interactions in the case of hadrons is distinctively larger

with respect to the photons, Geant4 assembles the lists of the various interactions under one *modular* physics list. For high-energy pions, the QGSP_BERT modular physics list is used, which stands for Quark Gluon String (QGS) Pre-compound model [186–189], utilizing the Bertini cascade [190, 191]. For the case of low-energy neutrons (MeV scale) the same library is used, but extended with the NeutronHP library for better description of the low-energetic processes (QGSP_BERT_HP).

B.2.3 Primary Generator Action

The primary generator action class defines the generation of primaries, that is, the beam or the radioactive source. For the purpose of the simulations presented in this thesis, three different primary generators have been implemented. For every case, a particle gun is instantiated and its properties are configured. The properties include the name, the energy and the momentum direction of the projectile particle, as well as the position of the particle gun in the World volume of the simulation.

In the case of the radioactive source, a particle gun is implemented on the external surface of the detector window in the center of the Y-Z plane. The gun emits photons, the energy of which corresponds to a characteristic X-ray of the radioactive source under study. To simulate the energy spectrum of a radioactive source, a random number is sampled from a uniform distribution. The random number is made to be within the range $[0, 1]$. This range is split in intervals corresponding to the probabilities of emission of a photon with a characteristic energy. If the random number falls within one of these intervals, the energy of the photon is set appropriately. Tables B.2 and B.3 summarise this configuration for the case of an Iron and a Cadmium radioactive source. Finally, the momentum direction of the primary particles is sampled by randomly selecting tracks within a conical shape starting from the point of the particle gun up until the center of the detector. Due to the very small distance between the particle gun and the detector, this configuration gives an stereo-angle to the photons from the source, thus not restricting them to hit the detector at only one point. The configuration of the primary generator for the case of photons is shown in Figure B.3a.

Furthermore, in the case of low-energy neutrons, the primary generator action is simulated to describe the configuration used for the MAMMA April 2015 test beam period on neutron beam. For the needs of this test beam, the chamber under study is placed 26cm away from the beam pipe, with the plane of the detector being vertical to the beam line. Then, the detector plane is rotated by 45° away from the vertical position. The neutron beam sprays the whole detector surface. Thus, the primary generator action class is configured with a particle gun that emits neutrons of 5.1 MeV (to match the experimental value) over the whole area of the detector. Instead of shifting the detector by 45° , the position of the particle gun and the momentum direction of the primaries is shifted appropriately. The configuration of the primary

Energy [keV]	Probability (%)	$n \sim \text{Uniform}[0, 1]$
0.64	1.0	$n \leq 0.01$
5.888	29.0	$0.01 < n \leq 0.30$
5.899	58.0	$0.30 < n \leq 0.88$
6.49	12.0	$n > 0.88$

Table B.2: The summary of the characteristic energies of a radioactive ^{55}Fe source spectrum. The second column represents the relative probability of emission of the specific energy peak, given that a photon is emitted. Finally the third column represents the interval between $[0, 1]$ in which when a random number belongs to it, the simulation software will set the photon energy.

Energy [keV]	Probability (%)	$n \sim \text{Uniform}[0, 1]$
2.980	9.6	$n \leq 0.096$
21.990	24.9	$0.096 < n \leq 0.345$
22.163	47.2	$0.345 < n \leq 0.817$
24.900	15.2	$0.817 < n \leq 0.969$
88.034	3.1	$n > 0.969$

Table B.3: The summary of the characteristic energies of a radioactive ^{109}Cd source spectrum. The second column represents the relative probability of emission of the specific energy peak, given that a photon is emitted. Finally the third column represents the interval between $[0, 1]$ in which when a random number belongs to it, the simulation software will set the photon energy.

generator for the case of neutrons is shown in Figure B.3b.

Finally, for the case of high-energy pions, the primary generator action is simulated to describe the configuration used in another MAMMA test beam. This time it was the September 2015 MAMMA test beam period which took place at SPS NA/H6 at CERN, testing the chambers under the pion beam. In this case, the incident beam is orthogonal to the plane of the detector. However, the profile of the pion beam is not point-like. On the contrary, it follows an I-beam ("pancake") shape, where on the transverse plane, the beam is focused in one direction, and de-focused on the other. From test-beam data, the width of the beam profile was estimated to be $20 \times 7\text{mm}$. Therefore, the particle gun is simulated to generate π^+ primaries of 120 GeV with a momentum direction orthogonal to the plane of the detector, but the starting point of the primaries can vary randomly by $20 \times 7\text{mm}$ around the center of the detector. The configuration of the primary generator for the case of neutrons is shown in Figure B.3c.

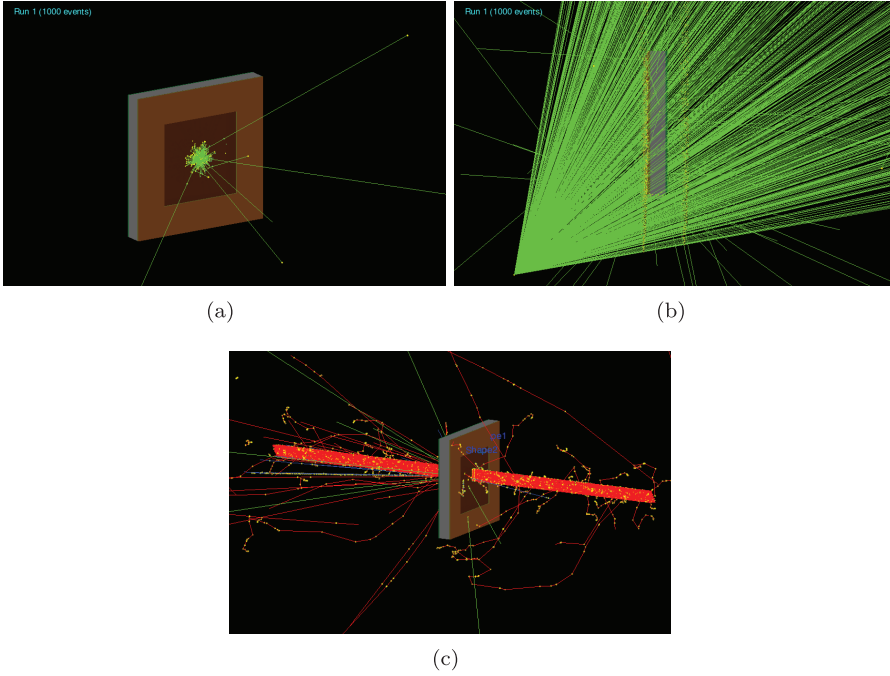


Figure B.3: The setup of the particle gun for the different processes simulated by the software. (a) Photons emitted from a radioactive source placed on top of the detector window, (b) neutrons spraying the detector surface with an angle of 45° , and (c) positive pion beam with a pancake shape, as delivered by the SPS accelerator.

B.2.4 Run and Event Action

Within the Geant4 framework, the `RunAction` and `EventAction` classes define what the algorithm should process at the start and at the end of each run and event respectively.

B.3 Physics with Photons

The first step on the presentation of the simulation software is the discussion on the tests performed with photon sources. As discussed in Section B.2.3, the radioactive ^{55}Fe and ^{109}Cd sources are simulated. Figures B.4a and B.4b, show the total energy deposited in the chamber as simulated by the two sources. In detail, Figure B.4a shows the spectrum of the iron source. The dominant peak at the 5.9 keV is the characteristic energy peak of this source. However, the peak at 2.9 keV does not originate directly from the Iron source. This peak is due to the Argon gas with which the detector is filled and a process called

argon escape. In this process, the primary photon from the Iron, ionises the argon gas which emits a photoelectron from its K-shell. The electron binding energy for the K-shell of the argon is 3.206 keV, the energy of the incoming photon is the characteristic of the source, thus the photoelectron should carry an energy of 2.9 keV, which is indeed the peak that is observed.

Similar is the case of the ^{109}Cd source in Figure B.4b. However, due to the fact that the energies of the Cadmium are an order of magnitude larger than of the iron, instead of a few peaks, a continuous spectrum is observed. Apart from the three energies of the source (as discussed in Table B.3), the peaks around 21.7 keV ($24.9 \text{ keV} - 3.206 \text{ keV}$), 19 keV ($22.163 \text{ keV} - 3.206 \text{ keV}$ and 18.8 keV ($21.990 \text{ keV} - 3.206 \text{ keV}$) are associated to the argon escape. In addition, the peaks observed in the energy range of 5.5 – 7.1 keV are attributed to the fluorescence process, which is simply characteristic X-rays generated from the material of the mesh (nickel, chromium and iron).

To simulate a real-life detector response, the spectra of the radioactive sources are smeared using a Gaussian distribution of $G(1, 0.15)$. This results to the plots shown in B.4c and B.4d for the Iron and Cadmium source respectively.

Trying to validate the simulation, two calibration runs from the MAMMA April 2015 test beam period are used. The electronics that were used to read out the chambers during the test-beams are the ones also used by the silicon tracker of the CMS detector, the APV25 [192]. The choice of the electronics is temporary since the micromegas-dedicated ones are still under development. These front-end electronics measures the total charge each detector strip collected in analog-to-digital converted (ADC) counts. In addition, the distribution of the charge in each bin, is split into several time bins, depending on the integration time of the electronics. This means that the full information of the energy deposited is not available. In fact, this effect can be illustrated in Figure B.5, which shows the distribution of ADC counts as a function of the number of injected (or primary) electrons. The not fully linear relation between the two quantities is shown. In addition, the fact that the distribution reaches a plateau and does not vary from there shows that above a certain number of induced charge, the electronics is not able to provide any energy resolution, but return a number around the maximum ADC one. However, the use of this electronics temporarily makes sense, since the purpose of the detector in ATLAS would be to offer tracking and triggering information, and is not going to be used as a calorimetry detector.

In addition to this, the APV25 electronics has a specific range in the ADC counts that it can return per each strip. This range is unfortunately fixed (ranging from 0-2000 counts). However, the absolute value of counts that the electronics would provide depends on the number of primary electrons and the gain of the detector. The electronics is designed for silicon detectors where the number of primary electrons is small, in a gaseous detector the number of primaries depend on the electron binding energy of the gas atoms, that in case of Argon is 26eV. Therefore, one would expect that the electronics are going to be partly saturated, since the number of ADC counts is proportional

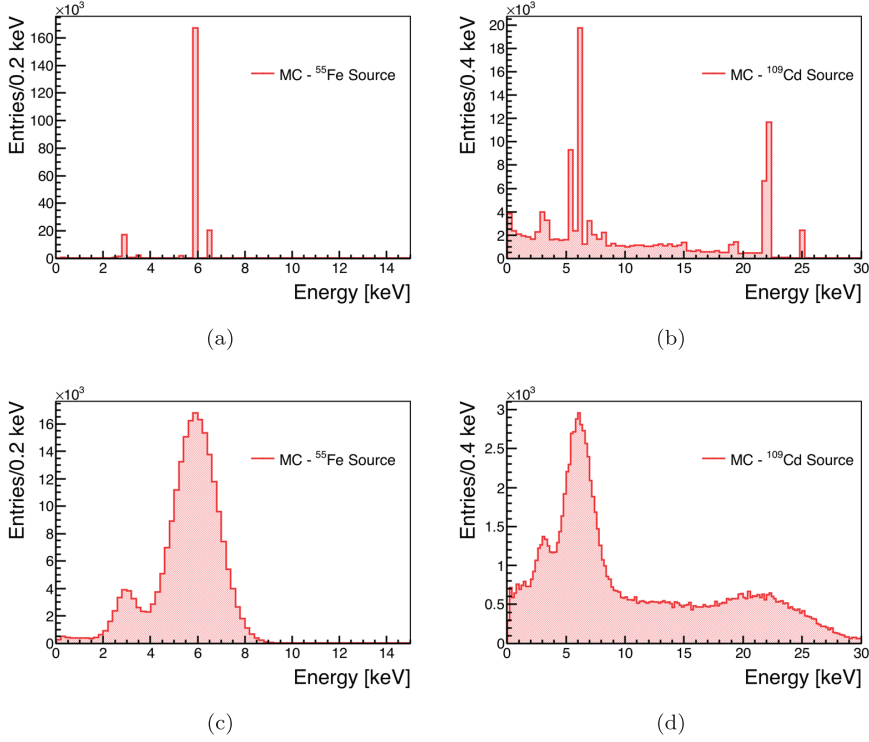


Figure B.4: The spectra of the sources as simulated in the software: (a) The one of the ^{55}Fe source as generated from the simulation software. (b) Similarly, of the ^{109}Cd source. (c) Smearing the ^{55}Fe spectrum shown in (a) using a $G(1, 0.15)$ distribution. (d) Smearing the ^{109}Cd spectrum shown in (b) using a $G(1, 0.15)$ distribution.

to the primary electrons. This means that after a certain number of primary electrons and due to the fixed range of counts per strip the electronics can return, the detector will not be able to fully reproduce the energy spectrum.

Consequently, one has to evaluate the deposited energy from the integrated charge provided by the electronics, having in mind that a few mis-matches are expected. To simulate the deposited energy in the detector per event, the maximum ADC value of each strip is taken. The sum of all the maximum values correspond to the integrated charge, which in some sense should be comparable to the deposited energy. With this assumption, Figure B.6a shows the integrated charge for the data using the ^{55}Fe source.

To validate the simulation, a conversion between the deposited energy in keV and the readout charge in ADC counts has to be found. For this reason, the energy values of the characteristic peaks in the spectrum of the iron, as

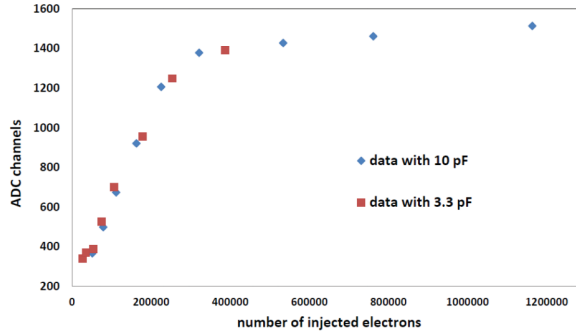


Figure B.5: A distribution of the ADC count that the APV25 electronics return as a function of the number of injected electrons. The trend in the distribution indicates at first the non linear response of the electronics. However, the most relevant information for the study presented here, is that above a certain value of injected charge, the response of the electronics arrives to a plateau, without increasing for large charge variations. This is indicative of the fact that the access to the full energy information is not possible with these type of front-end cards. The plot is taken from Ref. [193].

seen in Figure B.4, are matched to the ADC values of the peaks in the charge distribution for an iron run, as seen in Figure B.6a. In the distribution of data two quality cuts are applied to clean some of the electronic noise. These requirements are that single strip events are dismissed, to remove faulty events, as well as that the maximum charge per strip should be above the threshold of 100 ADC counts, to remove entries from fluctuations of the electronic noise.

Assuming a linear relation between the two units, one can extract a conversion matrix between them. This matrix is applied on the data collected under the same conditions but using a Cadmium source, to test the agreement between data and simulation. The overlayed plots for the Iron source are shown in Figure B.6b, while the same conversion applied on the cadmium source is shown in Figure B.6c.

The peaks of the spectra in the data match well the peaks in the Monte Carlo. At the low-end of the data distributions it can be observed that a small amount of noise still exists. From the shapes of the overlayed distributions, one would suspect that the response of the electronics is not fully linear, and consequently also the relation between the keV and the ADC units. This can be inferred from the fact that while the peaks of the data and MC distributions match almost perfectly, the width of the curves matches in one peak, while in the other is not in exact agreement.

Finally, one last observation is that in the Cadmium spectrum, the peak observed in the simulation at around 22keV is not apparent in the data. This is indicative of the fact that using the APV25 front-end electronics, the full

energy information cannot be accessed. To demonstrate this an independent experiment had been set up. Using the same chamber under the same conditions, the spectrum of the Iron source, with a characteristic energy at 5.9 keV is collected by the electronics, Figure B.7a. Then, the spectrum of a Copper X-ray gun, of a characteristic energy at 8 keV is also collected, Figure B.7b. The peaks in both distribution seem to be in the same region of the ADC counts distribution, while their energy responses are quite different. This means that using the X-ray gun, the electronics are saturated and cannot successfully acquire the total energy deposited. This is more clear in Figure B.7c, which shows the distribution of the maximum ADC counts collected per strip. The bump at the high values of the distribution demonstrates the saturation of the electronics, and the fact that a statistically significant number of events are falling into the high values of the ADC range of the electronics.

The simulation software managed to reproduce the detector response and therefore, the software can be considered validated in the case of photons. Due to the lack of the full energy deposited in the chamber, the upcoming studies with neutrons and pions are going to be validated only qualitatively, thus comparing the characteristics of the energy distributions in the simulation and in the data.

B.4 Physics with Neutrons

To study the behaviour of the chamber in the neutron environment, the detector is placed in front of a beam that sprays its surface in an angle of 45° , as discussed in Section B.2.3. Figure B.8 shows a picture of the experimental set up. The energy of the neutron beam is 5.1 MeV. This set-up corresponds to the MAMMA April 2015 Test-beam period. Figures B.9a and B.9b, show the deposited energy in the data (i.e. the integrated charge) collected in the test beam and in the Geant4 simulated events. From a qualitative perspective the simulated distribution looks very similar to the data. To further compare the trends, the two curves are overlayed on top of each other. The peak in the simulated distribution is used to convert the ADC counts to keV, while the two distributions are normalised in terms of events. Except for the fact that the low-energy part of the simulated distribution is missing in the data, due to thresholds set in the trigger chain that cannot be fully implemented in the simulation, the two curves follow the same trends. In the simulation, it is possible to disentangle the various physics processes that contribute to the deposited energy. Figure B.10 shows in different scales the various processes. At high values of the deposited energy, the elastic and inelastic hadron processes are dominant, while at lower values, the electromagnetic processes, such as energy deposited by photoelectrons and ionisations are more predominant.

In addition, Figure B.11 shows the energy that a collection of particles have left in the active area of the detector. For the purposes of illustration only a few of the particles are presented. Some particles illustrate a characteristic

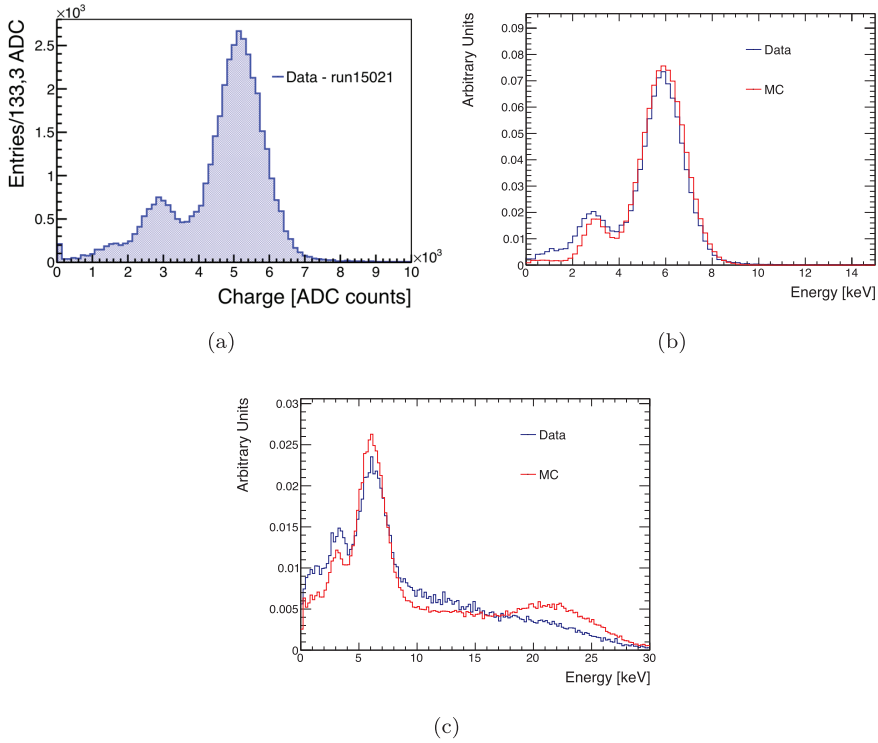


Figure B.6: (a) The spectrum of the ^{55}Fe source in data collected by the APV25 electronics. The plotted distribution corresponds to the integrated charge over the maximum ADC values of all strips per event. (b) Converting the ADC counts of the data to keV and comparing with the simulated MC sample. For the comparison, both data and MC distributions are normalised to unit area. (c) Applying the conversion as taken from the ^{55}Fe source to the ^{109}Cd radioactive source. The data are compared to the simulated MC sample. For the comparison, both data and MC distributions are normalised to unit area.

trend in their distribution. For example the step of the energy distribution of the Argon (Figure B.11a) is observable as expected.

Finally, to visualise the spatial distribution of the particles presented in Figure B.11, the software is able to plot their starting position. Figures B.12 and B.13 show the X-Y and Y-Z projection of this spatial distributions. It is interesting to see the different patterns appearing in these projections. For example, the distribution of the protons can provide a hint on the internal structure of the detector, as well as the geometrical position of the source. In detail, the mesh, the drift and the aluminium frame are visible. Furthermore, the fact that the neutrons hit the detector in a 45° angle, explains the fact that

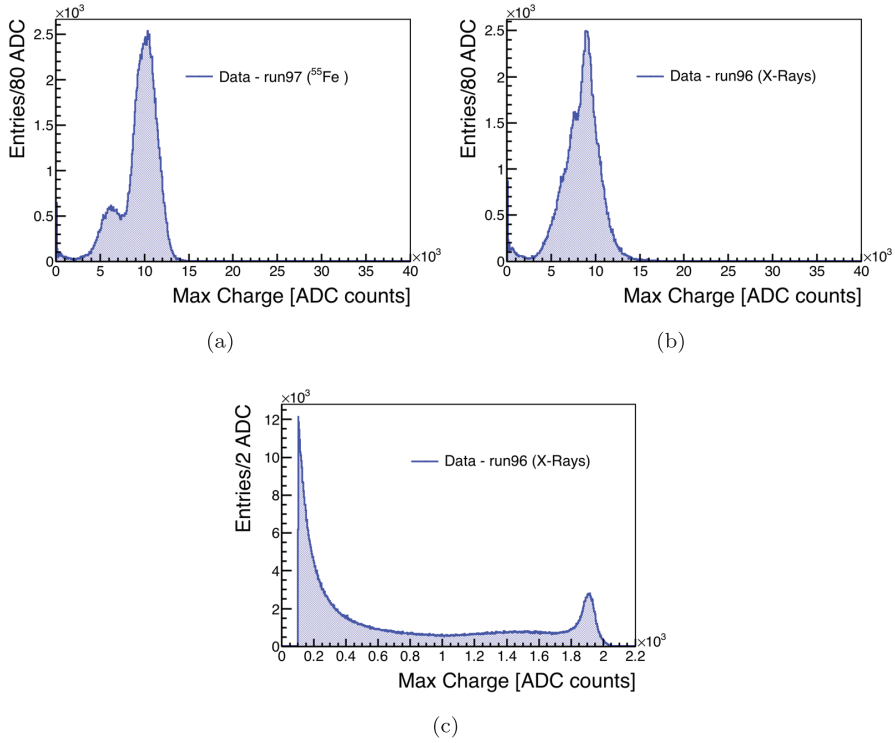


Figure B.7: (a) The spectrum of the ^{55}Fe source in data collected by the APV25 electronics. The plotted distribution corresponds to the integrated charge over the maximum ADC values of all strips per event. (b) Similarly, the spectrum of the Copper x-ray gun in data. The peak that corresponds to 8 keV is presented in almost the same ADC count as the 5.9 keV peak of the Iron source. (c) The distribution of the maximum charge per strip as a function of ADC counts. The bump at the far right of the curve is indicative of the saturation of the electronics, and therefore it signals the incapability to access precisely the full energy deposited in the chamber.

the starting position of most protons is the lowest right part of the detector (Figure B.12f). Similar is the case in Figure B.13f where the aluminium frame is noticeable in the scatter plot.

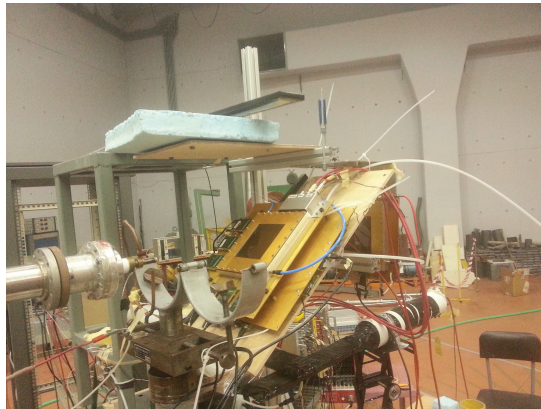
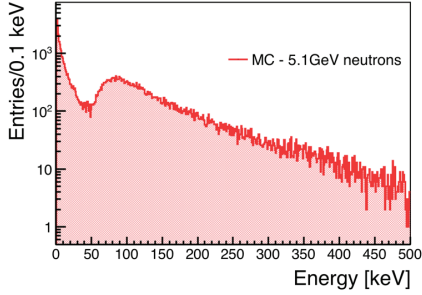
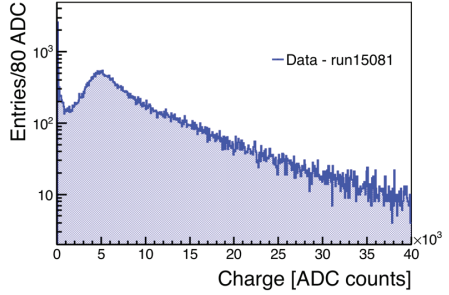


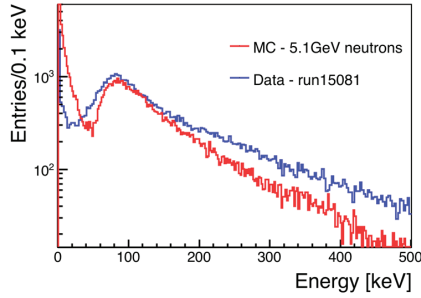
Figure B.8: A picture from the experimental set up of the MAMMA April 2015 test beam period. The resistive micromegas chamber is placed in a distance of 26cm away from the beam pipe and is rotated by 45° .



(a)

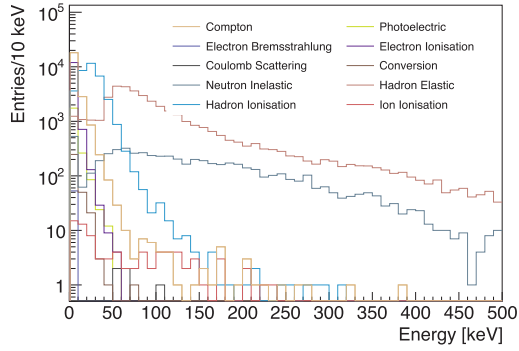


(b)

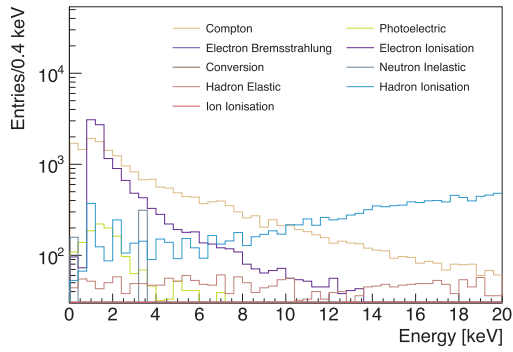


(c)

Figure B.9: (a) The distribution of the energy deposited in the active area of the simulated detector when placed in a 5.1 MeV neutron beam, with a 45° angle with respect to its surface. 2×10^9 primary neutrons have been generated. (b) The distribution of the charge collected by the APV25 electronics, when the chamber is placed in a 5.1 MeV neutron beam, with a 45° angle with respect to its surface. (c) A comparison of the distributions of (a) and (b).

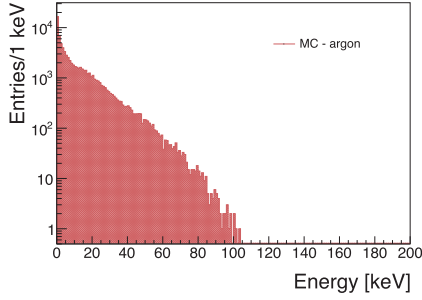


(a)

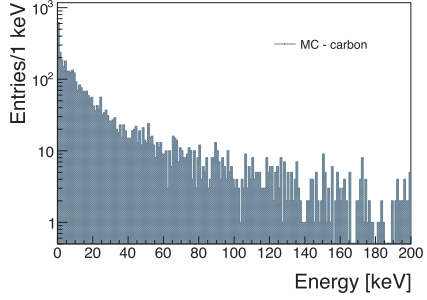


(b)

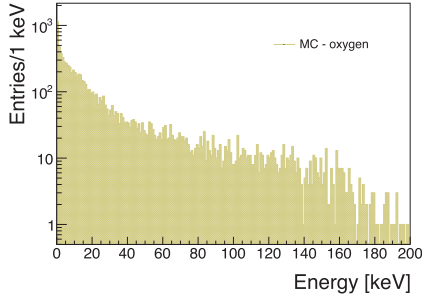
Figure B.10: The distribution of the energy deposited in the micromegas detector split per physics process in a large (a) and small (b) energy range, by 2×10^9 primary neutrons.



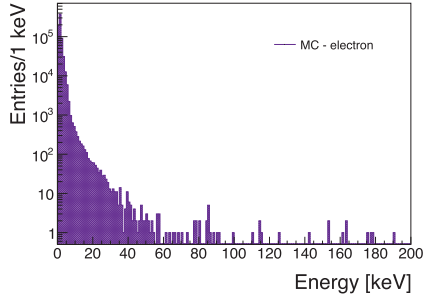
(a)



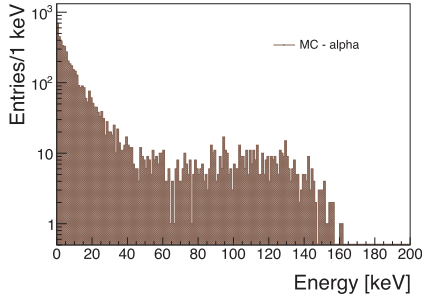
(b)



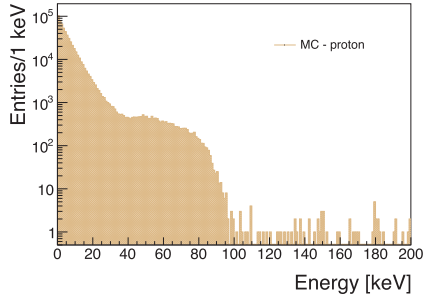
(c)



(d)



(e)



(f)

Figure B.11: The energy deposited in the detector by different types of particles: (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons. Characteristic trends of some distributions, as for example the step in the distribution of the Argon (a), are present.

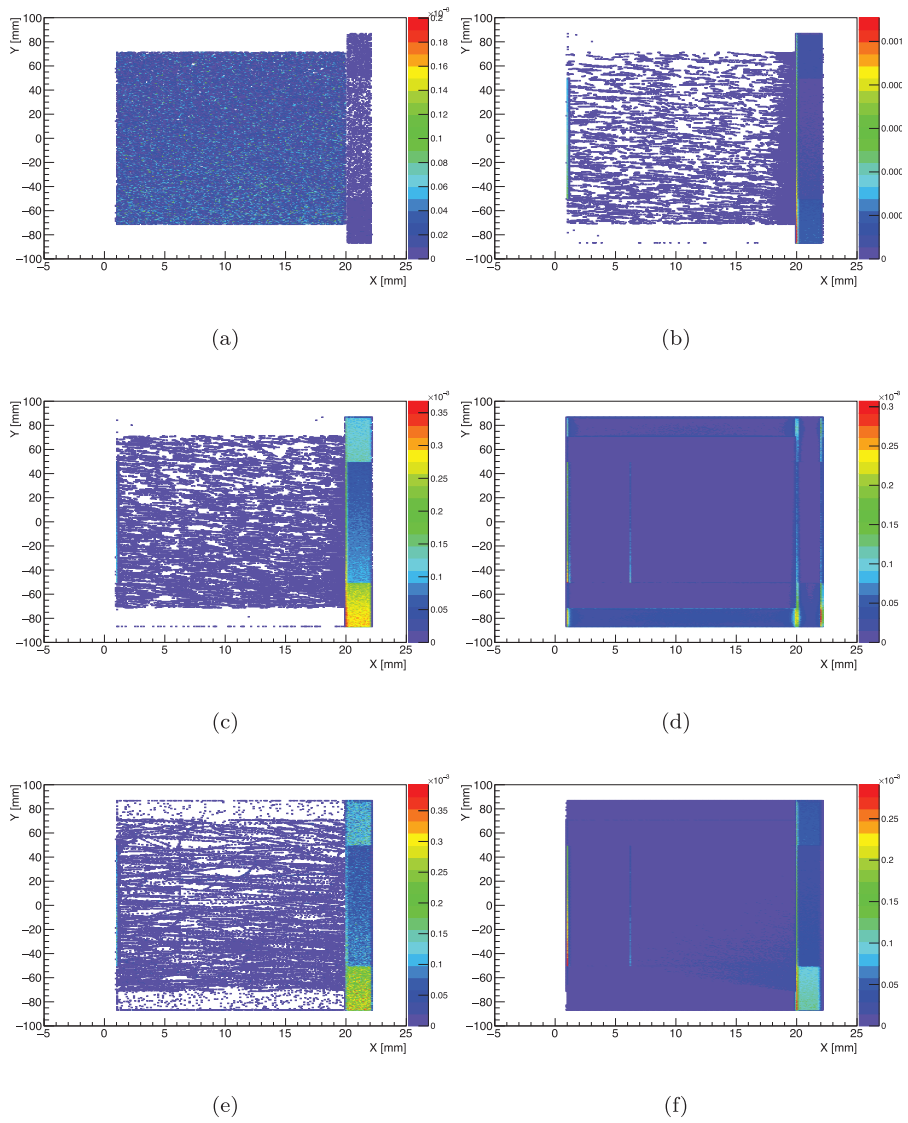


Figure B.12: The X-Y projection of the starting position of different particle types, in the case of a diagonal neutron beam colliding on a micromegas detector. The case of (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons are shown. Both dimensions are given in millimetres

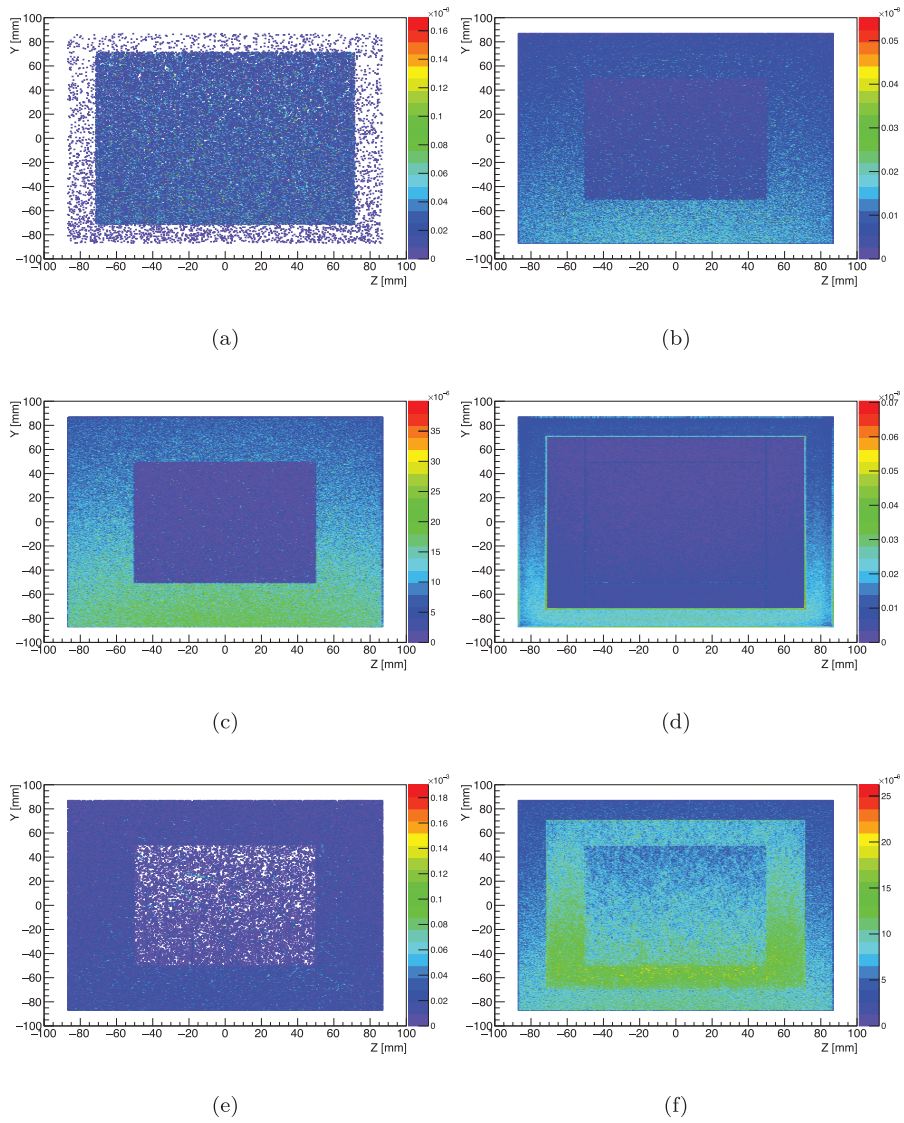


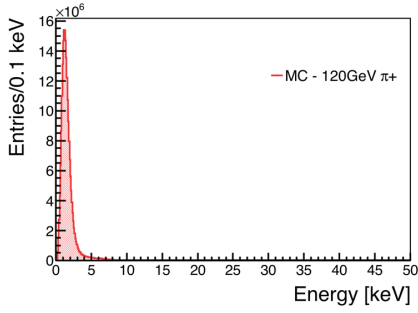
Figure B.13: The Y-Z projection of the starting position of different particle types, in the case of a diagonal neutron beam colliding on a micromegas detector. The cases of (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons are shown. Both dimensions are given in millimetres.

B.5 Physics with Pions

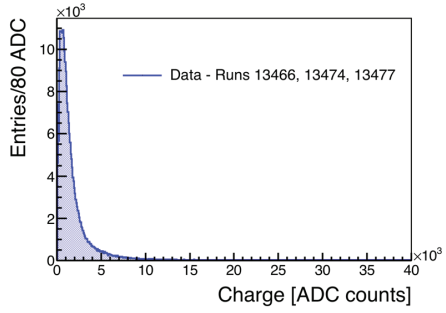
Using a different set-up for the primary generator action, the physics results of the MAMMA Test Beam September 2015 period can be simulated. In this Test Beam, the micromegas chamber is placed orthogonal in front of a π^+ beam of 120 GeV, as delivered by the SPS. The beam profile as delivered by the accelerator line is $20 \times 7\text{mm}$, as discussed in Section B.2.3. Figures B.14a and B.14b, show the deposited energy in the data (i.e. the integrated charge) and in the simulation. From a qualitative perspective the simulated and collected distributions look similar. To further compare the trends, the two curves are overlayed on top of each other. The peak in the Monte Carlo is used to normalise the horizontal axis (to perform the conversion between ADC counts and keV). Also, the two distributions are normalised in the same number of events. No simulation smearing is performed. The shape of the peak is reproduced, but the inability of the electronics to precisely measure the deposited energy, as well as the lack of description for the detector resolution, results in the wider data distribution. Furthermore, Figure B.15 shows the contributions of each physics process in the total deposited energy, in two scales. In the high-energetic region, the inelastic collisions of the π^+ beam with the atoms of the materials of the detector, seem to dominate the energy spectrum. On the other hand, at low energies, hadron ionisations and electromagnetic effects are dominant.

In addition to the total energy, Figure B.16 shows the energy only of a certain type of particle deposits in the chamber. Only a few of the particles are shown: the distributions from Argon, Carbon and Oxygen ions, together with the ones of electrons, protons and alpha particles.

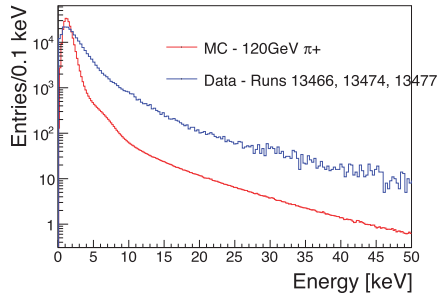
Finally, to visualise the spatial distribution of the particles presented in Figure B.16, their starting position is also plotted. Figures B.17 and B.18 show the X-Y and Y-Z projection of this spatial distributions, respectively. It is interesting to see the different patterns appearing in these projections. For example, the distribution of pions (Figure B.17f) depicts the focus of the beam only in the center of the detector. This is also shown in Figure B.18f, where the beam profile in the transverse plane is more apparent.



(a)

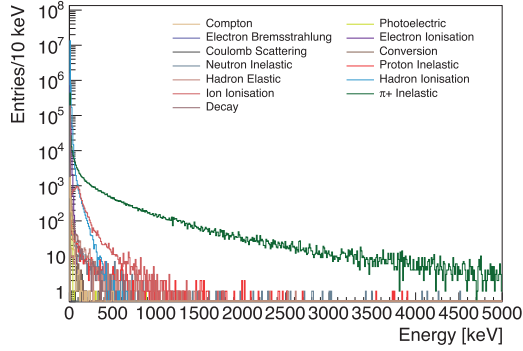


(b)

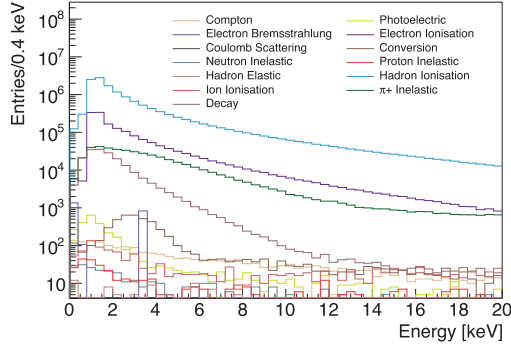


(c)

Figure B.14: (a) The distribution of the energy deposited in the active area of the simulated detector when placed orthogonal in front of the π^+ beam of SPS. 2×10^8 primary particles have been generated. (b) The distribution of the charge collected by the APV25 electronics, when the chamber was subjected to the same conditions. (c) An comparison of the distributions of (a) and (b) with the ADC to keV conversion done with the single peak point, while the two distributions are normalised to the same number of events.

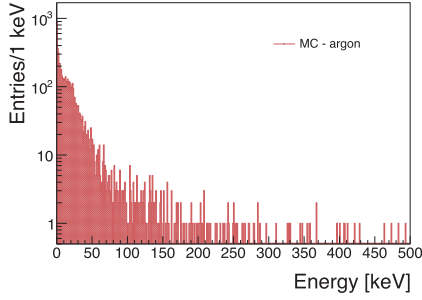


(a)

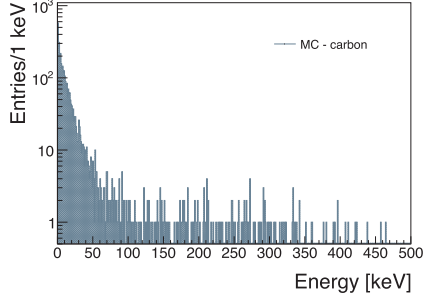


(b)

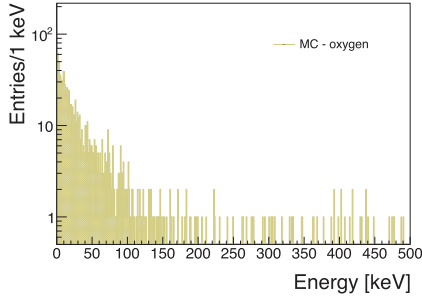
Figure B.15: The contributions of the various physics processes in the total deposited energy in the micromegas detector from a π^+ beam of 120 GeV. 2×10^8 primary particles have been generated. Different processes dominate the high- (a) and low-energy (b) regions.



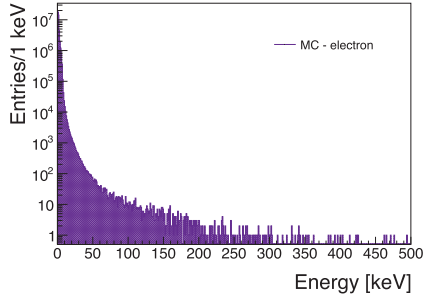
(a)



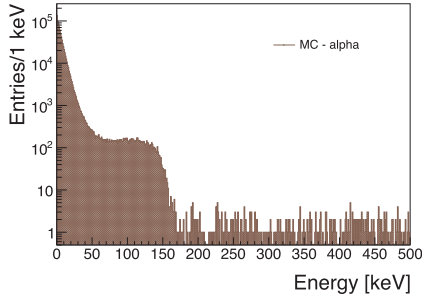
(b)



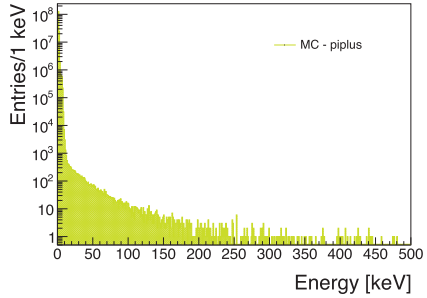
(c)



(d)



(e)



(f)

Figure B.16: The energy deposited in the detector by different types of particles, when the micromegas detector is placed in front of the π^+ SPS beam. The cases of (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons are shown.

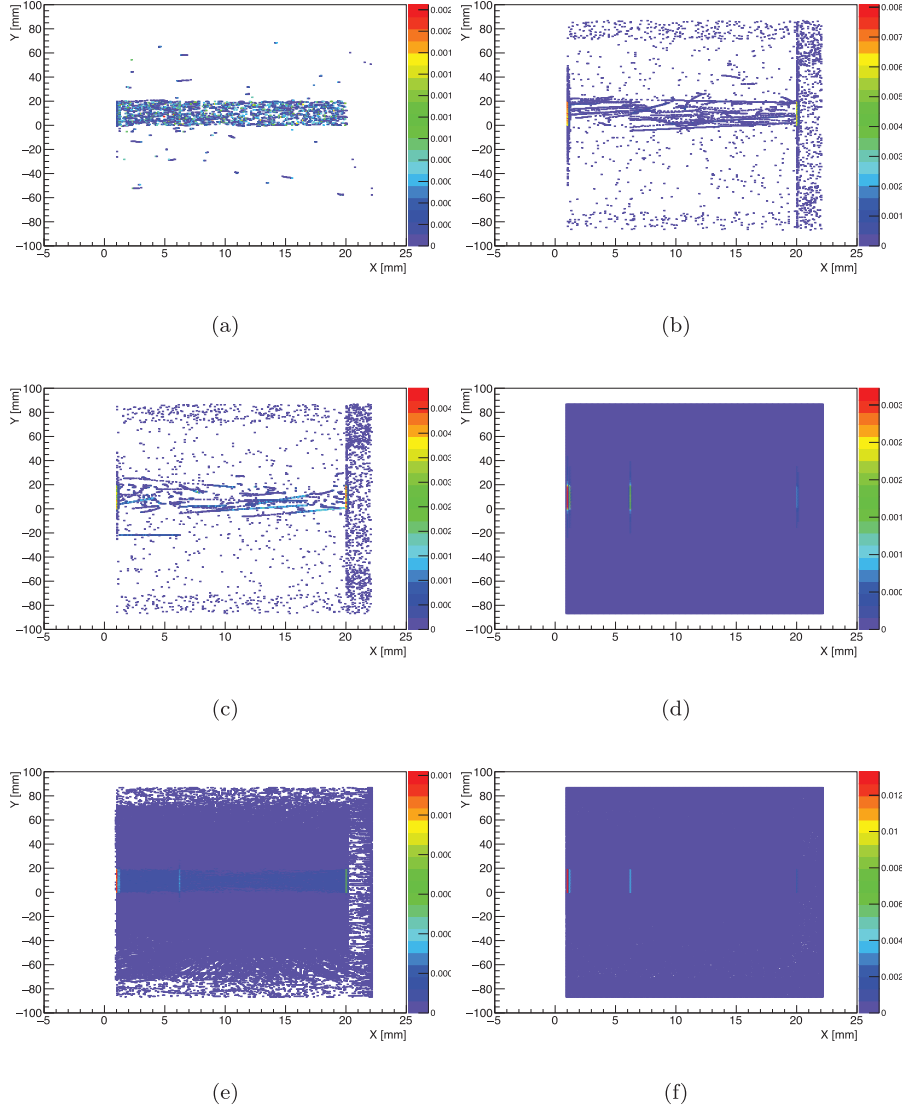


Figure B.17: The X-Y projection of the starting position of different particle types when the micromegas detector is placed vertically in front of the SPS π^+ beam. The cases of (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons are shown. Both dimensions are given in millimetres.

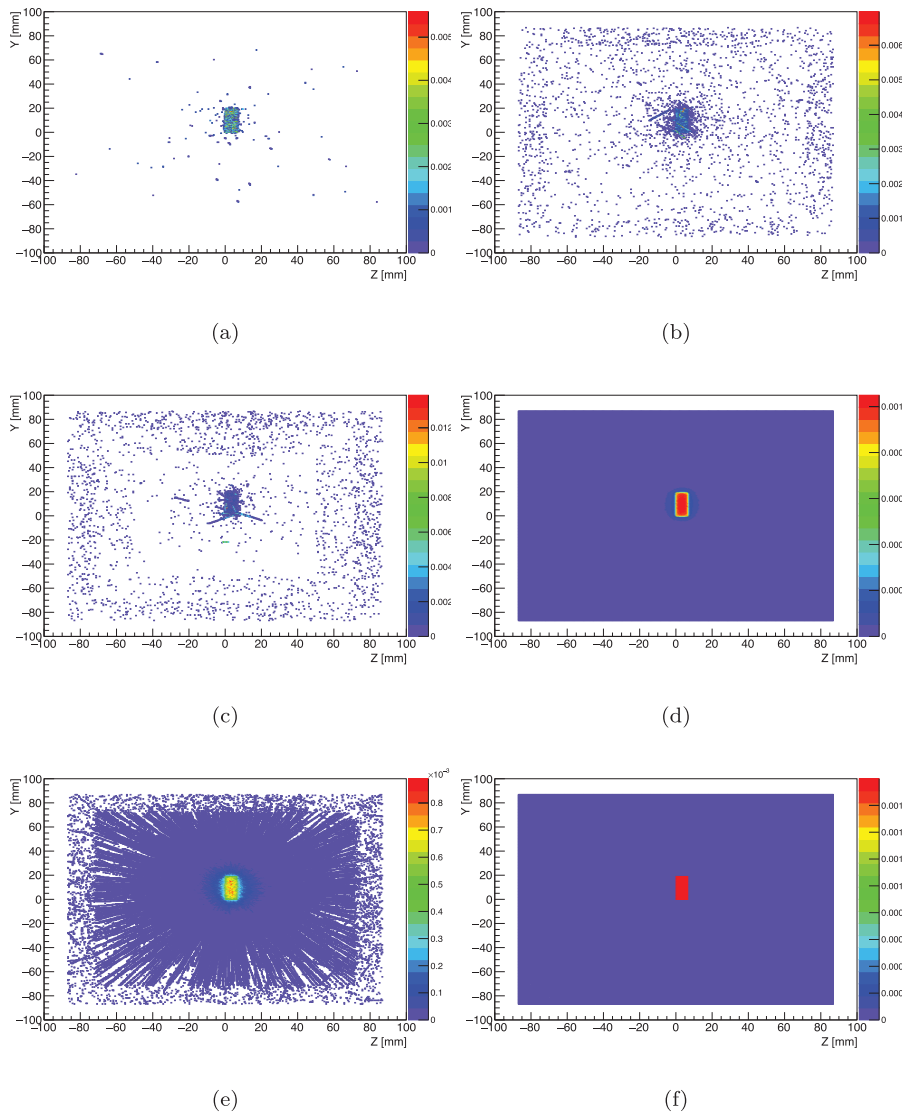


Figure B.18: The Y-Z projection of the starting position of different particle types when the micromegas detector is placed vertically in front of the SPS π^+ beam. The cases of (a) Argon; (b) Carbon; (c) Oxygen; (d) electrons; (e) alpha particles; (f) protons are shown. Both dimensions are given in millimetres.