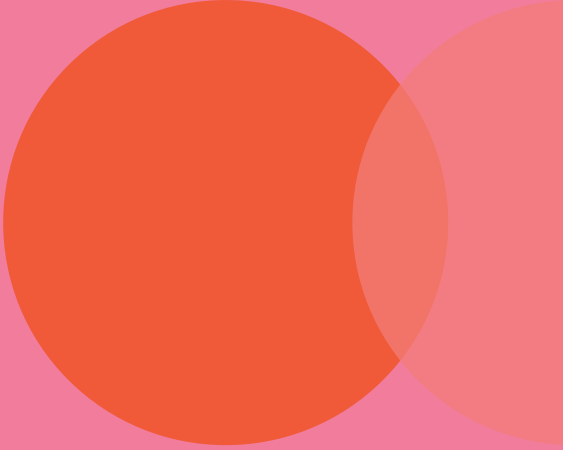




DETERMINING THE

HIGGS^{BOSON} WIDTH

in the diphoton decay channel with the ATLAS experiment.

Ashley McDougall



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Determining the Higgs boson width in the diphoton decay channel with the ATLAS experiment

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« Quel sol che pria d'amor mi scaldò 'l petto,
di bella verità m'avea scoperto,
provando e riprovando, il dolce aspetto »

DANTE

Contents

1	Introduction	1
2	The Standard Model of particle physics and the Higgs boson	5
2.1	The Standard Model theory	5
2.1.1	Quantum electrodynamics	8
2.1.2	Quantum chromodynamics	9
2.1.3	Electroweak interactions	12
2.1.4	The origin of mass	13
2.2	SM Higgs boson properties and experimental overview	17
2.2.1	Mass	17
2.2.2	Width	18
2.2.3	Higgs boson production modes	20
2.2.4	Higgs boson decay channels	21
2.2.5	Experimental discovery and property measurements	23
3	Determination of the Higgs boson width	27
3.1	Direct methods to measure the Higgs boson width	28
3.2	The off-shell method using $H^* \rightarrow ZZ$ decays	30
3.2.1	Experimental results	34
3.3	Interferometry using the $H \rightarrow \gamma\gamma$ channel	36
3.3.1	$gg \rightarrow (H \rightarrow)\gamma\gamma$ interference at the LHC	36
3.3.2	Sub-dominant interference contributions	40
3.3.3	Interference calculations beyond NLO	42
3.3.4	Calculating the mass shift, $\Delta m_{\gamma\gamma}$, and extracting Γ_H	43
3.3.5	Shape fit over $m_{\gamma\gamma}$ distribution	48
4	The Large Hadron Collider and the ATLAS experiment	51
4.1	The Large Hadron Collider	51
4.1.1	Accelerator complex	52
4.1.2	Cross-sections and luminosity	54
4.1.3	Data-taking periods	55
4.2	The nature of hadronic collisions	56
4.3	Event generation and simulation	57

4.4	The ATLAS detector	60
4.4.1	Coordinate system	62
4.4.2	Tracking system	63
4.4.3	Calorimetry system	65
4.4.4	Muon spectrometer	71
4.4.5	Trigger and data acquisition system	72
5	Particle reconstruction with ATLAS	75
5.1	Tracks and vertices	76
5.2	Electron and photon reconstruction	77
5.2.1	Topo-clusters	78
5.2.2	Superclusters	80
5.2.3	Electrons and photons for analysis	81
5.3	Electron and photon energy calibration	82
5.3.1	Energy calibration uncertainties	86
5.4	Photon performance	89
5.4.1	Photon identification	89
5.4.2	Photon isolation	92
5.5	Electron performance	93
5.6	Conclusion	95
6	Determining the Higgs boson width in the diphoton decay channel	97
6.1	General $H \rightarrow \gamma\gamma$ analysis strategy	97
6.2	Data and MC simulated samples	99
6.2.1	Data samples	99
6.2.2	MC samples	100
6.2.3	Simulated events with non-SM Γ_H values	106
6.3	Event selection	108
6.3.1	Diphoton primary vertex	109
6.3.2	Event selection	111
6.4	Event categorisation	113
6.4.1	Optimisation studies	118
6.4.2	Analysis event categorisation	121
6.5	Signal model	123
6.5.1	m_H parametrisation	126
6.5.2	Sensitivity to the Higgs boson width	126
6.6	Interference model	126
6.6.1	Interference functions with different widths: Morphing	128
6.6.2	Parametrising the total interference yield	132
6.7	Background model	134

6.7.1	Spurious signal test and background function results	135
6.8	Systematic uncertainties	138
6.8.1	Experimental uncertainties	140
	Signal variations due to the photon energy calibration	140
	Interference variations due to the photon energy calibration	142
	Yield uncertainties	144
6.8.2	Cross-section and luminosity	145
6.8.3	Scale and PDF uncertainties	146
6.8.4	Interference cross-section scale-factor uncertainty	148
6.8.5	MC generator initialisation parameters	149
6.8.6	Parton shower algorithm	150
6.8.7	Modelling bias uncertainties	151
6.9	Statistical model	154
6.10	Results	159
6.10.1	Expected results	159
6.10.2	Observed results	162
6.11	Measurement prospects and future improvements	163
6.12	Conclusion	165
7	The High Luminosity Large Hadron Collider	167
7.1	Planned ATLAS detector upgrades for the HL-LHC	168
7.2	The Inner Tracker	170
7.2.1	The ITk strip detector	171
7.2.2	The ITk end-cap global support structure	173
7.2.3	A mock-up of the end-cap global structure	175
7.3	Mechanical alignment of the ITk strip end-cap global structure mock-up	176
7.3.1	Introduction to LVDTs	177
7.3.2	Accuracy of the LVDT system	179
7.3.3	Calibration of the LVDT coils	181
7.3.4	Systematic uncertainties	183
7.3.5	Attaching the LVDTs to the mock-up	186
7.3.6	Validation of the LVDT-measured displacement	189
7.3.7	Thermal deformation measurement results	190
7.3.8	Discussion and interpretation	193
7.3.9	Conclusion	194
7.4	Mechanical alignment of the ITk strip end-cap stiffening disks	194
7.4.1	Calibration studies	196
7.4.2	Experimental set-up	197
7.4.3	Calculation of the sagitta parameter	199
7.4.4	Results	199

7.4.5 Conclusion	201
7.5 Conclusion	201
8 Conclusion	203
Summary	213
Samenvatting	222
References	234
A Event selection impact on the interference $m_{\gamma\gamma}$ distribution	235
B Impact of interference effects on the signal shape	237
C Signal and interference kinematic distributions	239
D Distributions required to define the interference morphing function	243
E Additional distributions required for systematic uncertainties	247
E.1 Shape systematic uncertainties evaluated in category 2	247
E.2 Analytical functions describing the PES and PER interference systematic variations	249
E.3 Evaluate interference morphing functions in category 2 used for the analysis . . .	253
F LVDT measurement validation tests	255
F.1 LVDT measurement validation	255
Acknowledgements	257

1 | Introduction

Understanding the universe at the most fundamental level is the purpose of research in the field of experimental particle physics. The Standard Model (SM) of particle physics is the theoretical framework that describes all subatomic particles and the forces that mediate their interactions (corresponding to three of the four fundamental forces in nature). Predictions made by the SM theory have been extensively experimentally scrutinised over the last years. Despite this, recent experimental measurements and theoretical advancements indicate this theory is only an approximation to a more general description of nature. Most notably through its failure to account for the observed matter-antimatter asymmetry in the universe today, the nature of dark matter, the origin of neutrino masses, and the unification with gravity - being the fourth fundamental force.

The Large Hadron Collider (LHC) located at the European Organisation for Nuclear Research (CERN) is the biggest particle collider in the world, operating at the frontiers of both energy and knowledge. The ATLAS detector is the largest experiment at the Large Hadron Collider, which is used to see the particles produced by two colliding proton beams. The primary goals of the ATLAS physics programme are to determine all properties of the Higgs boson accurately and to conduct searches for new physics beyond what the present theory predicts. The Higgs boson particle is an excellent tool to perform these measurements, as it is related to a majority of the free parameters in the theory. In the last decade since its 2012 discovery [1], members of the ATLAS collaboration, including myself since 2017, have been precisely measuring properties of the Higgs boson to check for consistency with the SM predictions [2]. Given the large number of SM free parameters the Higgs boson is connected to, it is well-poised to be used as a probe for new physics, with the aim of answering the multitude of open questions in modern day particle physics.

Numerous Higgs boson properties have been measured thus far through analysing the data collected by the ATLAS detector during the first two operational runs of the LHC. The Higgs boson mass has been measured in both of the original discovery decay channels, $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$, now with per-mille precision. The mass parameter is particularly important since it is not predicted by the SM theory, and thus must be experimentally determined. Furthermore, many additional Higgs boson parameters are only determined by the theory once the Higgs boson

mass value is known; the Higgs boson decay width is one such parameter. The dominant five production modes have been observed, as well as many (though not all) of the possible Higgs boson decay modes. In particular, couplings to the first and second generation fermions have not yet been observed.

The Higgs boson total decay width, directly related to the particle's lifetime, is one of the remaining Higgs properties to measure. Deviations from the SM predicted value of 4.09 ± 0.16 MeV [3], could hint at potential sources of new physics, as it would either indicate the couplings to SM particles are not as expected, or the Higgs boson couples to some new non-SM particle.

This thesis presents an analysis of the Higgs boson decay width using the $H \rightarrow \gamma\gamma$ decay channel where interferometry, a novel measurement technique, is implemented [4]. Although the di-photon final state has a relatively clean detector signature, this is an extremely challenging measurement given the very narrow intrinsic width of the SM Higgs boson, when compared to the detector resolution, which is on the order of 1 to 2 GeV depending on the kinematic selections applied. A non-standard measurement technique is employed in an attempt to measure the Higgs boson width, which makes use of quantum interference effects between the resonant signal and the continuum background processes. In general, quantum interference occurs between processes which possess the same initial and final state particles. The presence of this interference causes a shift in the di-photon invariant mass distribution, and the size of this shift is directly related to the width of the decaying Higgs boson. The analysis presented in this thesis makes use of the data collected during the Run 2 data-taking period of the LHC, which occurred between 2015 and 2018. During this time, protons were collided at a centre of mass energy of 13 TeV, and in total 140.1 fb^{-1} of data was recorded.

To gain a better understanding of the Higgs boson's properties and to conduct detailed searches for physics beyond the SM, the existing LHC will be upgraded to a higher luminosity version (HL-LHC) by 2029 [5]. This collider will be able to access rare processes by increasing the instantaneous luminosity up to a factor of 7.5 times the current value. The current LHC dataset is merely 4% of the total size which will be collected by the end of the HL-LHC data-taking period. In conjunction with this increase in luminosity of the LHC, many of the existing ATLAS detector sub-components will be upgraded. Preparation for these upgrades is already well underway.

Thesis outline and statement of personal contributions: The research presented in this dissertation has been undertaken as a member of the ATLAS collaboration, which now has over 3000 members. Below is an outline of the chapters contained in this thesis, where I have also summarised in the following sections my direct personal contributions to each area of work I present. Naturally, the level of detail discussed for each topic is directly related to my level of personal contribution in that area, and its relevance to my research topic.

Chapter 2 provides an introduction to the Standard Model Higgs boson particle, as well as a broad review of the current experimental status in the field of Higgs physics. Chapter 3 presents a theoretical introduction to the possible techniques available for measuring the width of the Higgs boson, where the benefits and limitations of each method are discussed. Chapter 4 introduces the Large Hadron Collider and the ATLAS detector. The main concepts necessary to perform physics measurements at a hadron collider are also described. Chapter 5 provides a general overview of the procedure used to reconstruct, identify and perform the energy calibration for photons (and electrons) measured by the ATLAS detector.

Chapter 6 presents the analysis undertaken to measure the width of the Higgs boson, in the di-photon decay channel. I was the main analyser for the entirety of this analysis, and thus was the dominant individual responsible for every aspect of the analysis. This included preparing and validating a new method to generate Monte Carlo simulations for the processes involved, development of the analysis strategy, and optimisation of the selection criteria to enhance the analysis sensitivity. I performed the statistical fit, as well as evaluated the theoretical and experimental systematics, in order to achieve the final result. I was appointed as one of two *analysis contacts*, alongside a postdoctoral researcher, Stefano Manzoni. I was also the editor of the ATLAS internal documentation for this analysis. Aside from myself, five people in total, contributed to components of this analysis in various capacities. The content of this chapter, which contains the measured sensitivity to the Higgs boson width, is the main experimental result of this thesis. A journal paper summarising these results is currently in progress, which will constitute the first published result using this measurement technique by either the ATLAS or CMS collaborations.

Chapter 7 presents the research I undertook related to the upgrade of the existing ATLAS inner detector for the HL-LHC. I was responsible for developing a suitable alignment monitoring system to perform mechanical alignment studies on one component of the Inner Tracker (ITk) mechanical support structure. The alignment system used to conduct this research was set-up, tested and validated by myself, with the intention of it being used as part of the quality control and quality assurance procedures during the production phase of these mechanical support structures.

Chapter 8 provides concluding remarks on the research presented in this thesis.

2 | The Standard Model of particle physics and the Higgs boson

The Standard Model (SM) of particle physics is the theoretical framework encapsulating all known elementary particles, and the interactions between them. Since its conception, this theory has evolved through theoretical advancements as well as experimental measurements, and now stands as one of the most rigorously experimentally verified theories in physics to date. Despite the consistent agreement between predictions made by the SM theory, and the experimental results, there are a plethora of open questions in modern day particle physics which cannot be explained by this theory as it stands. This chapter contains an overview of the SM theory, summarises briefly the current status of Higgs boson measurements, and provides context for the analysis presented in this thesis. The particles and interactions described by the SM will be outlined in section 2.1 including the mechanism behind mass generation in the SM. An overview of Higgs boson phenomenology will be outlined in section 2.2 as well as the current experimental status of Higgs boson property measurements.

2.1 The Standard Model theory

The SM is a relativistic quantum field theory (QFT) described by the Lie groups associated to *quantum chromodynamics* ($SU(3)_C$) and the unification of electrodynamics with the electro-weak force ($SU(2)_L \times U(1)_Y$), and is summarised in equation 2.1. It is a Lorentz invariant theory which is constructed by demanding local gauge invariance of the following non-Abelian gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y, \quad (2.1)$$

where C is the colour charge quantum number of the $SU(3)$ group, L denotes couplings to left-handed fermions only, and Y is the hypercharge quantum number of the $U(1)$ group.

Forces and *matter* are the two fundamental building blocks of the universe, which in the context of a QFT, are defined in terms of quantum fields that permeate the entire universe. It is the quantisation of these fields which defines the elementary particles which are considered point-like and

Fermion generations					
	1st	2nd	3rd	Bosons	
Quarks	1/2 2/3 2.2 MeV <i>u</i> up	1/2 2/3 1.3 GeV <i>c</i> charm	1/2 2/3 172.8 GeV <i>t</i> top	1 0 0 <i>γ</i> photon	0 2/3 125.1 GeV <i>H</i> Higgs
	1/2 -1/3 4.7 MeV <i>d</i> down	1/2 -1/3 93 MeV <i>s</i> strange	1/2 -1/3 4.2 GeV <i>b</i> bottom	1 0 0 <i>g</i> gluon	
	1/2 1 511 keV <i>e</i> electron	1/2 1 105.7 MeV <i>μ</i> muon	1/2 1 1.8 GeV <i>τ</i> tau	1 1 91.2 GeV <i>Z</i>	
Leptons	1/2 0 0 <i>ν_e</i> <i>e</i> neutrino	1/2 0 0 <i>ν_μ</i> <i>μ</i> neutrino	1/2 0 0 <i>ν_τ</i> <i>τ</i> neutrino	1 0 80.4 GeV <i>W[±]</i>	Spin Charge Mass Symbol Name

Figure 2.1: Elementary particles of the Standard Model of particle physics. In total the SM is comprised of 12 fermions, five types of force carrying bosons - one being the Higgs boson, responsible for mass generation. The spin, electric charge, mass and particle name is indicated.

carry an intrinsic angular momentum known as spin. Particles are grouped into either one of *fermions* or *bosons*, depending on whether their intrinsic spin is an odd multiple of $1/2$, or is an integer number respectively. Fermions are what constitute the matter particles, whereas the bosons are the force carriers of the SM and mediate the interactions between fermions. The particle content of the SM is shown in Figure 2.1.

Fermions are categorised into either quarks or leptons, depending on whether they possess the required charge to interact via the strong nuclear force or not. Overall the SM contains six quarks, and six leptons, which are organised into three generations of doublets depending on the magnitude of their mass. All ordinary visible matter in the universe, is entirely comprised of the first generation fermions; the atom is made up of electrons, up-type quarks and down-type quarks. The reason behind why the second and third generation fermions exist at all is still unknown. The three lepton generations are each made up of one charged, and one neutral particle known as neutrinos. In the SM theory, neutrinos are predicted to be massless. Experimental measurements of neutrino oscillations have shown that neutrinos do in fact have a non-zero mass, and several results including from cosmology have placed an upper limit on the mass difference between pairs of neutrinos, and the sum of neutrino masses [6]. All fermion particles have an antimatter

counterpart, which differs from the particle only in terms of the sign of the electromagnetic charge. For example, the antimatter particle corresponding to the electron is the positron, which has a +1 electric charge. Neutrinos are the only fermions which have zero electric charge, and as such may be their own antimatter particle (known as Majorana neutrinos) [7], though this has not been experimentally verified yet.

Three of the four fundamental forces of nature are described in the SM, which includes the weak nuclear force, the strong nuclear force, and the electromagnetic force. Gravity is not included as there is no consistent quantum formulation, however as it is the by far weakest of the forces (roughly 33 orders of magnitude weaker than the nuclear force) it can be safely ignored when considering high-energy particle processes. The strong force is mediated by the gluon, g , and the charge associated to the strong force is known as *colour*. Interactions via the strong force are described in section 2.1.2. The weak force is mediated by the neutral Z^0 , and charged $W^\pm$ bosons, and as the name suggests is the weakest of the three forces included in the SM. Electroweak interactions (the unification of electromagnetism with weak interactions) is outlined in section 2.1.3. The Feynman diagrams displayed in Figure 2.2 illustrate the coupling of the gauge bosons to the fermions.

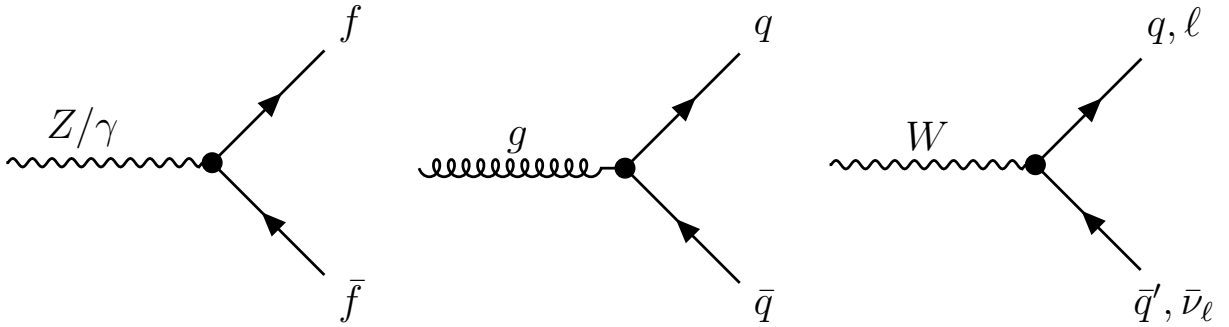


Figure 2.2: Feynman diagrams depicting the three types of interactions described by the SM. The leftmost diagram illustrates the Z and γ coupling to fermions, the centre corresponds to a gluon decaying to a same flavour quark-antiquark pair ($q\bar{q}$), and the rightmost diagram depicts the decay of a charged W boson into either a $q\bar{q}'$ pair of different flavours, or a lepton and antineutrino of the same flavour.

The photon is a particularly important particle, since the main analysis presented in this thesis will focus on proton-proton collisions which result in two photons being produced in the ATLAS detector, since it is the final state which allows us to determine the Higgs boson width via interferometry. The photon is a spin-1 gauge boson, has no electric or colour charge, and is massless. The electromagnetic force is mediated by the photon, γ , and has infinite range. The detection, and subsequent reconstruction and energy calibration, of photons with the ATLAS detector is presented in Chapters 4 and 5 respectively. The quantum field theory describing the interaction of electrically charged particles is reviewed in section 2.1.1.

2.1.1 Quantum electrodynamics

Quantum electrodynamics (QED), was the first quantum field theory to be developed and is described by the simplest gauge group, $U(1)_Q$. QED describes the interactions of charged particles, which arise through requiring local gauge invariance under transformations of the $U(1)_Q$ group. To illustrate how this works, we can write the Lagrangian describing a freely propagating electron (or any fermion in general) as:

$$\mathcal{L}_e = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi, \quad (2.2)$$

where m is the mass of the electron, ψ represents the electron field, γ^μ are the gamma matrices, and ‘freely’ indicates the potential term is zero. Local gauge invariance for QED means that the equations of motion do not change under the following transformation:

$$\psi \rightarrow \psi' = e^{iq\chi(x)}\psi \quad (2.3)$$

where $\chi(x)$ is a spacetime dependent phase and q is the coupling strength. To make the Lagrangian invariant under such transformations, additional terms must be introduced. More specifically, the derivative must transform as a covariant derivative, that is $\delta_\mu \rightarrow D_\mu = \delta_\mu - iqA_\mu$, and the introduction of a vector boson field (A_μ), which represents a massless spin-1 boson such as the photon, and transforms as:

$$A_\mu \rightarrow A_\mu + \frac{1}{q}\partial_\mu\chi(x) \quad (2.4)$$

for any function $\chi(x)$. The result is that in this theory not only is there a vector field, but it also couples to the fermion with strength q . Physically, this can be interpreted as the electric charge of the fermion ψ . An example of a QED interaction is given by the Feynman diagram in Figure 2.3, where the coupling is labelled at the two interaction vertices.

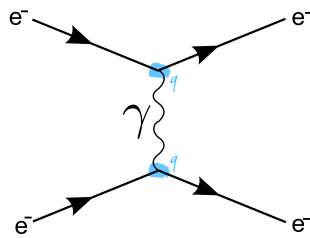


Figure 2.3: A Feynman diagram depicting an example QED process; electron scattering via the exchange of a photon, known as Møller scattering.

Substituting the above equation 2.3 and 2.4 transformations into equation 2.2 we obtain the interaction Lagrangian for QED:

$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi \quad (2.5)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the field strength tensor for electrodynamics, and the covariant

derivative is defined as $\not{D} = \gamma^\mu(\partial_\mu - iqA_\mu)$ in units where $\hbar = c = 1$. It is important to note that there are no mass terms of the form $\frac{1}{2}m^2 A_\mu A^\mu$ present for the gauge field because such a term breaks local gauge invariance, and hence requires the force mediator of QED to be massless. Maxwell's equations for electromagnetism are recovered from equation 2.5 in the absence of any sources, then $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$. The QED Lagrangian is not part of the equation 2.1 symmetry of the SM; it emerges following the spontaneous symmetry breaking of the $SU(2)_L \times U(1)_Y$ group. The mechanism behind this symmetry breaking is described in section 2.1.3.

2.1.2 Quantum chromodynamics

Quantum *chromodynamics*, QCD, describes the interactions of coloured particles, where the prefix *chromo* derives from the Ancient Greek $\chi\rho\omega\mu\alpha$ (*khōroma*) meaning colour. Generally speaking, QCD describes the interactions of quarks and gluons, which are the only particles in the SM that have colour charge. QCD is of particular relevance for physics conducted with the ATLAS experiment, considering the LHC collides beams of protons at the ATLAS detector interaction point.

QCD is based on the non-Abelian $SU(3)$ gauge symmetry. Quarks carry one of the three colour charges labelled red (R), blue (B) or green (G), and likewise antiquarks carry an anticolour charge, antired ($\bar{R}$), antiblue ($\bar{B}$) and antigreen ($\bar{G}$). Any observed bound state is required to be colourless, which is obtained by combining colour-anticolour components such that the overall net charge is zero. The strong force is mediated by eight massless force carriers known as gluons, which along with quarks, are the only particles in the SM that carry colour charge. The QCD Lagrangian is defined by:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} + i\bar{\psi}\gamma^\mu(\partial_\mu - ig_s G_\mu^a T^a)\psi, \quad (2.6)$$

where ψ is the quark fermion field, the gluon field is defined in terms of the field strength tensor $G_{\mu\nu}^a$, g_s is the coupling constant for $SU(3)_C$ defined by $g_s = \sqrt{4\pi\alpha_s}$, and T^a are the set of matrices representing the group generators. The index a refers to the gluon colour states and thus should be summed from 1 to 8. The force carriers of QCD themselves carry a colour charge; a consequence of this feature is the ability to self-interact via both cubic and quartic couplings. Such self-interactions amongst the gluons result in a dynamically changing coupling constant for the strong force, which depends on the energy scale. As can be seen in equation 2.7, the value of the strong coupling constant varies as a function of the energy, parametrised by μ^2 . The fact that the coupling constant changes according to the energy scale considered is known as the *running* of the coupling. The strength of the strong force is dictated by the coupling constant, $\alpha_s(\mu^2)$, defined as:

$$\alpha_s(\mu^2) = \frac{12\pi}{(33 - 2n_f)\ln\left(\frac{\mu^2}{\Lambda_{QCD}^2}\right)}, \quad (2.7)$$

where n_f is the number of quark flavours contributing at a given energy scale, and $\Lambda_{QCD} \sim 200$ MeV quantifies the energy scale where the perturbative QCD coupling diverges; the perturbative

expansion is valid only in the energy regime where $\mu^2 \gg \Lambda_{\text{QCD}}$. The three elementary QCD interactions are shown in Figure 2.1.2, which includes the quark-gluon coupling, and cubic and quartic couplings between gluons.

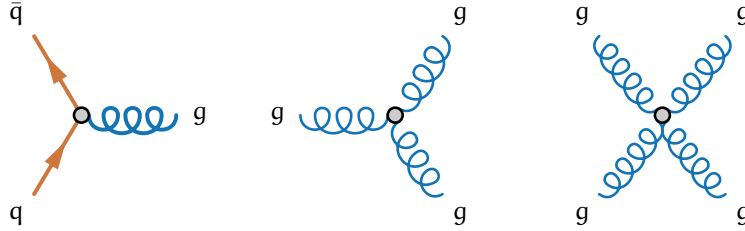


Figure 2.4: Three Feynman diagrams depicting QCD interactions: quark radiating a gluon, cubic gluon coupling, and quartic gluon coupling.

Two unique and fundamental properties of QCD are uncovered when considering either the very high energy, or the very low energy extremes. The general trend of equation 2.7 as μ^2 increases is that α_s decreases. In the extreme case where $\mu^2 \rightarrow \infty$, $\alpha_s \rightarrow 0$ which is known as *asymptotic freedom*. This property physically manifests itself when considering ultra high energies (synonymous with very short distances between quarks and gluons) for example within the nucleus, the partons are essentially free. The dependance of α_s on the energy scale μ^2 has been experimentally verified to agree with QCD predictions, achieved by measuring α_s at different energy scales. This behaviour shown in Figure 2.5, where the current world average for the strong coupling constant, at the energy scale of the Z boson mass, is $\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$ [6].

In the low energy case, when μ^2 is very small, α_s becomes exceedingly large. This behaviour is known as *confinement*, and is responsible for bounding quarks together inside *hadrons*. A hadron, which refers to a colourless composite particle made of quarks, are comprised of two or three quarks known as *mesons* or *baryons* respectively. Bound states of five quarks also exist, known as pentaquarks. As of yet, no free quarks or free gluons have been found to exist. In general, any process which produces a free quark in the final state will radiate gluons and subsequently *hadronise*, producing a collimated shower of energetic hadrons known as a *jet*. This occurs for all quarks except the top quark which is so heavy that it decays ($\text{BR}[t \rightarrow W^+ b] \sim 100\%$) before the free quark hadronises.

The proton is one example of a hadron, more specifically a baryon, as it is comprised of two up-type quarks and one down-type quark, held together by gluons. Hadrons in general are comprised of two main components; the *valence* quarks and the *sea* of virtual quarks and gluons. Valence quarks are defined by the quark content of the hadron, and carry all relevant quantum numbers; for the proton the three valence quarks are thus *uud*. The sea is defined by interactions between gluons, as well as virtual $q\bar{q}$ pairs, which may be produced in gluon interactions. The notion that the internal substructure of the proton is more than just the valence quarks is nicely illustrated by

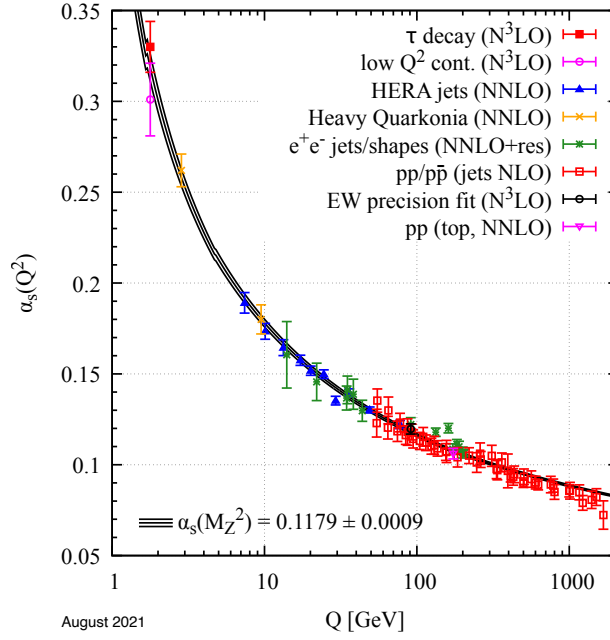


Figure 2.5: Summary of the experimental determination of α_s as a function of the energy scale, Q . For each experimental measurement displayed, the order in QCD perturbation theory used for the calculation of α_s is indicated in brackets [6].

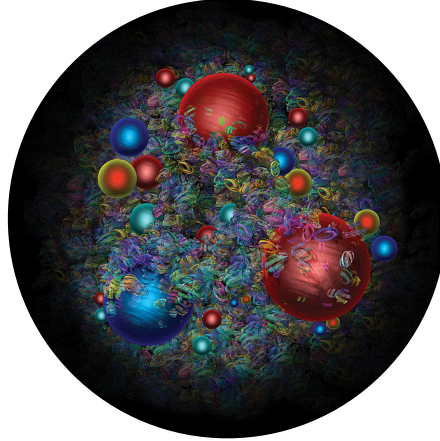


Figure 2.6: An artist's interpretation of the proton substructure. The proton, being a baryon, is comprised of three fundamental quarks: uud . The two largest red spheres represent the two up type valence quarks, whilst the one large blue sphere is the down type valence quark. These sit amongst a sea of quarks and gluons, as is the nature of quantum chromodynamics. Image credit: D. Dominguez, CERN.

an artistic impression of the proton substructure displayed in Figure 2.6. Rather, it is a dynamic system of sea quarks and gluons continuously popping in and out of existence. The observed flavours of the virtual quark pairs produced are dependent on the energy scale with which the hadron is probed.

The importance of the valence quarks (m_v) versus the sea contributions can be illustrated by considering the proton mass (m_p). Equation 2.8 presents the total mass of the proton, and equation 2.9 lists the sum of the three valence quark masses. The quark mass values are taken from the SM values listed in Figure 2.1.

$$m_p = 938.3 \text{ MeV} \quad (2.8)$$

$$m_v = 2.3 \text{ MeV} + 2.3 \text{ MeV} + 4.8 \text{ MeV} = 9.4 \text{ MeV} \quad (2.9)$$

The valence quark masses contribute a measly 1% of the total proton mass; it is the binding energy that defines the proton mass, not the sum of the valence quarks. These peculiar features of QCD are of particular importance when conducting physics analyses with the LHC, given the colliding beams are made of protons. Section 4.2 will discuss this further, focusing on the phenomenology of proton-proton collisions, and the mechanisms behind how such processes are predicted and simulated.

2.1.3 Electroweak interactions

The Glashow-Salam-Weinberg model [8, 9] unifies the electromagnetic and weak interactions by requiring local gauge invariance under:

$$SU(2)_L \times U(1)_Y \quad (2.10)$$

The subscript L refers to the fact that the weak force couples to left-handed fermions only, discovered through a series of experimental observations which included nuclear β decays, the muon decay ($\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$), and the absence of $\pi^- \rightarrow e^- + \bar{\nu}_e$ decays. The subscript Y stands for *hypercharge*, the generator of the $U(1)_Y$ group. The hypercharge cannot be directly interpreted as the electric charge q , as defined in QED since they are not equivalent, though are related through the Gell-Mann-Nishijima formula $Q = I_3 + Y/2$ as a consequence of electroweak symmetry breaking. Q is the electric charge of the hadron, and I_3 is the third component of the weak isospin.

The physical fields associated with the γ , charged $W^\pm$ and neutral Z bosons of the SM arise through imposing local gauge invariance of the group defined in equation 2.10. Initially there are four generators associated with this group, three gauge fields from the $SU(2)_L$ group: $\{W_1, W_2, W_3\} \in SU(2)_L$, and one from $U(1)_Y$: $\{B\} \in U(1)_Y$, which need to be massless to maintain local gauge invariance. These however do not correspond to the physical fields observed experimentally; this will be further discussed in section 2.1.4.

2.1.4 The origin of mass

The Brout-Englert-Higgs (BEH) mechanism is responsible for mass generation in the SM, and was developed predominantly in 1964 by P. Higgs [10], R. Brout and F. Englert [11, 12]. To accommodate the acquisition of mass, the SM Lagrangian is extended by introducing a complex $SU(2)_L$ doublet, ϕ , with an associated term in the Lagrangian of the form:

$$\begin{aligned}\mathcal{L}_{\text{Higgs}} &= (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \\ &= (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2,\end{aligned}\tag{2.11}$$

where the field is defined as

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix},\tag{2.12}$$

in terms of four real scalar fields ϕ_i ($i = 1, \dots, 4$). The potential term $V(\phi)$ in equation 2.11 has two free parameters, μ^2 and λ . The shape of the $V(\phi)$ can take different forms depending on the respective signs of these parameters. Choosing $\mu^2 < 0$ and $\lambda > 0$ yields the shape depicted in Figure 2.7, noting that λ must be positive to yield a state of minimum energy (i.e. a vacuum).

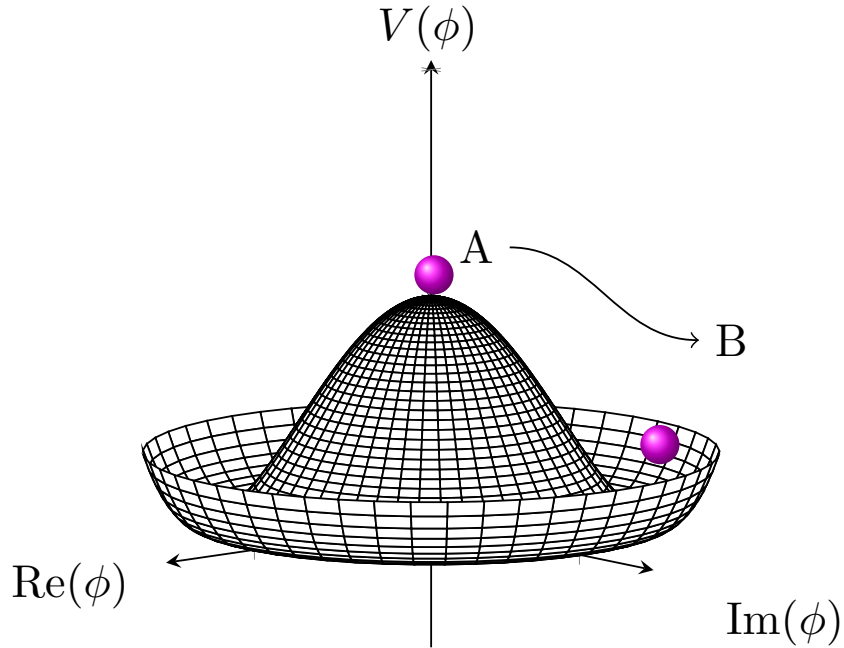


Figure 2.7: Shape of the Higgs potential, $V(\phi)$, when requiring $\mu^2 < 0$ and $\lambda > 0$. The global minimum has infinitely many solutions; the ball labelled at position B depicts one of them. This minimum does not occur at $\phi = 0$, rather at the vacuum expectation value, $v = \sqrt{-2\mu^2/\lambda}$.

In the case where $\mu^2 < 0$, the global minimum value of the potential, $V(\phi)$ occurs at

$$\phi^\dagger \phi = \frac{-\mu^2}{\lambda} \equiv \frac{v^2}{2}, \quad (2.13)$$

where v is called the *vacuum expectation value* (*vev*). Choosing ϕ which satisfies equation 2.13 has infinitely many solutions; this can be seen visually in Figure 2.7, where the point labelled B presents one example solution. One such minimum can be chosen by setting $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3 = v$, which conserves electric charge and ensures the photon remains massless (as is observed in nature). Substituting this choice into equation 2.12, the field components become:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.14)$$

A consequence of this non-zero *vev* is that the potential $V(\phi)$ around the vacuum is not invariant under $SU(2)_L \times U(1)_Y$. The symmetry of this group has thus been spontaneously broken; this is known as *electroweak symmetry breaking* (EWSB).

Now consider an expansion of ϕ around the minimum at the *vev*, then equation 2.12 becomes:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_1(x) + i\eta_2(x) \\ v + h(x) + i\eta_4(x) \end{pmatrix}, \quad (2.15)$$

where the introduced radial degree of freedom $h(x)$, and the three circular degrees of freedom (so-called Goldstone fields) $\eta_1(x)$, $\eta_2(x)$ and $\eta_4(x)$ parametrise this small deviation in ϕ_1 - ϕ_3 space. Choosing the unitary gauge allows for the definition of $\phi(x)$ expressed in 2.15 to be reduced to:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (2.16)$$

where the remaining real field $h(x)$ is identified as the Higgs field. Substituting this expression for the scalar field back into the Higgs Lagrangian from equation 2.11, the Lagrangian then yields:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & \frac{1}{2}(\partial_\mu h \cdot \partial^\mu h) + 0 \cdot A_\mu A^\mu \\ & + \left(\frac{g}{2}\right)^2 (v + h)^2 W_\mu^+ W^{\mu-} + \frac{1}{2} \left(\frac{g}{2\cos\theta_W}\right)^2 (v + h)^2 Z_\mu Z^\mu \\ & + \frac{\mu^2}{2}(v + h)^2 - \frac{\lambda}{4}(v + H)^4. \end{aligned} \quad (2.17)$$

As the transition to the minimum occurs at $\phi \neq 0$, the mass eigenstates corresponding to the physical $W^\pm$ and Z fields are generated, in addition to the newly introduced H field. The $W^\pm$

bosons are defined in terms of the W_1 and W_2 fields from section 2.1.3 as:

$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp W_2), \quad (2.18)$$

while the neutral B and W_3 states mix according to the Glashow-Salam-Weinberg theory to define the physical photon A_μ field and the Z boson field as a linear combination of the B and W_3 states, parametrised by the *Weinberg* weak mixing angle θ_W . These are defined as:

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \quad (2.19)$$

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \quad (2.20)$$

Expanding the potential terms (from equation 2.11) contained in the last line of the Higgs Lagrangian in equation 2.17 results in:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}}^{\text{pot.}} &= \frac{\mu^2}{2}(v+h)^2 - \frac{\lambda}{4}(v+h)^4 \\ &= -\lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4 + \frac{1}{4}\lambda v^4, \end{aligned} \quad (2.21)$$

where the mass term for the Higgs boson is identified as:

$$m_H = \sqrt{-2\mu^2} = v\sqrt{2\lambda}. \quad (2.22)$$

A neutral spin-0 Higgs boson particle, h is defined to be the excitation of the introduced Higgs field, with mass m_H according to equation 2.22. In addition to this mass term, there are also two self-interaction terms present, namely the $-\lambda v h^3$ and $-\frac{1}{4}\lambda h^4$ terms, which correspond to the cubic and quartic interactions of the Higgs boson respectively.

It is through this BEH mechanism that the $SU(2)_L \times U(1)_Y$ gauge symmetry is spontaneously broken, and the $W^\pm$ and Z bosons obtain mass. The second two terms from the Higgs Lagrangian in equation 2.17, contain the mass terms for the $W^\pm$ and Z^0 bosons, as well as define the couplings between the vector bosons and the Higgs field. The masses of the gauge bosons are extracted from the coefficient of the VV terms, where V represents the relevant gauge boson field (W, Z). Since there is no such term for the A_μ field, the photon remains massless. The mass terms for the vector bosons are:

$$m_W = \frac{g v}{2}; \quad (2.23)$$

$$m_Z = \frac{g v}{2 \cos\theta_W} = \frac{m_W}{\cos\theta_W}. \quad (2.24)$$

The interaction coupling strength is proportional to the mass of the vector boson, obtained using the coefficients of the respective VVh terms in equation 2.17. This results in a coupling strength

between the W bosons with the Higgs boson of:

$$g_W = \frac{2m_W^2}{v}, \quad (2.25)$$

while for the Z boson the strength is:

$$g_Z = 2\cos(\theta_W) \frac{m_Z^2}{v}. \quad (2.26)$$

The Feynman diagrams shown in Figure 2.8 display the interaction between the Higgs boson and the $W^\pm$ and Z^0 bosons respectively.

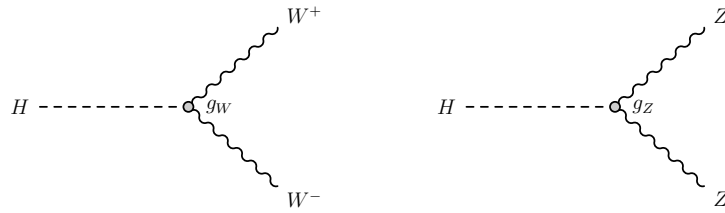


Figure 2.8: Feynman diagrams depicting the interaction of the Higgs boson with the two massive gauge bosons of the SM.

Fermion masses:

The introduction of mass terms for fermions is forbidden in the SM theory since left and right handed components are mixed, which results in gauge invariance being broken. The mass terms can be introduced in a gauge invariant way by using the previously introduced complex Higgs field, in equation 2.16. The BEH mechanism is then responsible for the generation of fermions masses in the SM, through the inclusion of specific $-g_f \bar{\psi}_L \phi \psi_R$ vertices, which are invariant under $SU(2)_L \times U(1)_Y$, and couple the Higgs field to fermions, known as *Yukawa* couplings. These fermion-Higgs couplings are defined in the SM Lagrangian by including terms of the form:

$$\mathcal{L}_f = -g_f [\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L], \quad (2.27)$$

for a given fermion f . Using the Higgs field after EWSB, the fermion Lagrangian can then be written as:

$$\mathcal{L}_f = -\frac{1}{\sqrt{2}} g_f \left[\bar{\psi}_L \begin{pmatrix} 0 \\ v+h \end{pmatrix} \psi_R + \bar{\psi}_R (0, v+h) \psi_L \right]. \quad (2.28)$$

To extract more explicitly an example fermion mass, consider the electron, denoted e . When $f = e$, the Lagrangian from equation 2.28 becomes:

$$\begin{aligned}\mathcal{L}_e &= -\frac{1}{\sqrt{2}}g_e \left[(\bar{e}, \bar{e})_L \begin{pmatrix} 0 \\ v+h \end{pmatrix} e_R + \bar{e}_R(0, v+h) \begin{pmatrix} v \\ e \end{pmatrix}_L \right] \\ &= -\frac{g_e(v+h)}{\sqrt{2}} [\bar{e}_L e_R + \bar{e}_R e_L] \\ &= -\frac{g_e}{\sqrt{2}} v \bar{e} e - \frac{g_e}{\sqrt{2}} H \bar{e} e.\end{aligned}\tag{2.29}$$

From equation 2.29, the coefficient of the first term corresponds to the mass term for the electron, so $m_e = \frac{g_e v}{\sqrt{2}}$, while the second term describes the electron coupling to the Higgs boson field, which as it turns out is proportional to the mass. This is true generally for all fermions, where $m_f = \frac{g_f v}{\sqrt{2}}$. Rearranging, the general expression for the coupling between the Higgs boson and fermion field is:

$$g_f = \sqrt{2} \frac{m_f}{v},\tag{2.30}$$

where g_f is the fermion-Yukawa coupling and m_f corresponds to the fermion mass. Without the introduction of such terms, fermions would remain massless in the SM. The values for m_H , m_f , and the vev (recall this is defined in terms of μ and λ in equation 2.13 which define the shape of the Higgs potential) are not predicted by the SM theory, and as such must be experimentally determined. As will be presented in section 2.2.5, the Higgs boson mass has been measured now to a per-mille precision. Although all the fermion mass values have been experimentally determined, the couplings of the relevant Yukawa interactions between all six fermions and the Higgs boson have not all been measured. The current experimental status of such couplings will also be presented in section 2.2.5, where the main aim is to ascertain if the measured fermion couplings to the Higgs boson are indeed proportional to m_f .

2.2 SM Higgs boson properties and experimental overview

This section will present an overview of our current theoretical and experimental knowledge of the Higgs boson's properties. The most relevant properties will be introduced in sections 2.2.1 and 2.2.2. The main SM Higgs boson production modes at the LHC are presented in section 2.2.3; the expected decay channels are described in section 2.2.4. Experimental measurements of the Higgs boson's properties will be outlined in section 2.2.5, with a specific focus on the results obtained by the ATLAS experiment.

2.2.1 Mass

The SM does not predict values for the two free parameters defining the Higgs boson potential: μ and λ , typically expressed in terms of the Higgs mass m_H and the vev as per equation 2.22. Since

there is no theoretical prediction, the Higgs boson mass must be measured experimentally. In July 2012, the ATLAS and CMS experiments at CERN announced their individual discoveries of a Higgs boson particle with mass ~ 125 GeV; further details on this and subsequent measurements will be discussed in section 2.2.5.

2.2.2 Width

In addition to the mass, another important particle property is the decay lifetime, τ . Few particles in nature are stable, most of them - the Higgs boson included - are unstable and subsequently decay to other particles. It is a fundamental property of quantum mechanics that, due to Heisenberg's uncertainty principle ($\Delta t \Delta E \geq (\hbar/2)$), any unstable particle (so finite lifetime), does not have an exactly defined mass value. The decay lifetime of the particle is inversely proportional to the total decay rate, Γ , as:

$$\tau = \frac{\hbar}{\Gamma}. \quad (2.31)$$

For any given elementary particle with more than one allowed decay mode, Γ corresponds to the total decay rate and is defined by the sum of all partial decay rates:

$$\Gamma = \sum_{i=0}^n \Gamma_i, \quad (2.32)$$

where i runs over all possible decay channels of the particle. The invariant mass distribution follows that of a relativistic Breit-Wigner where the total decay rate is defined by the irreducible *width* of the distribution, known as the *total decay width*. Here the term irreducible has been used to point out that this is in contrast to for example the detector resolution effects, which also causes a broadening of the invariant mass distribution, though this is a reducible effect that can in principle be reduced to zero if the detector is calibrated with infinite precision. The intrinsic width of the invariant mass distribution however is a property of the decaying particle itself. Stable particles, such as the proton or electron, have $\Gamma = 0$. The Breit-Wigner distribution is defined as:

$$f(m_{\gamma\gamma}; \Gamma, m_H) = \frac{1}{\pi} \frac{\Gamma/2}{\Gamma^2/4 + (m_{\gamma\gamma} - m_H)^2}, \quad (2.33)$$

where the mean of the distribution corresponds to the Higgs boson mass, m_H , and the width of the peak is the Higgs boson decay width, Γ .

In the case of the Higgs boson, the total decay width can be defined by summing all predicted $H \rightarrow \xi\bar{\xi}'$ decay channels, where $\xi\bar{\xi}'$ denotes the allowed final states, to obtain the following

expression:

$$\Gamma_{\text{total}} = \Gamma_H^{\text{SM}} = \sum_{\zeta\zeta'} \Gamma_{H \rightarrow \zeta\zeta'} \quad (2.34)$$

$$\begin{aligned} &= \Gamma(H \rightarrow b\bar{b}) + \Gamma(H \rightarrow \tau\tau) + \Gamma(H \rightarrow gg) \\ &+ \Gamma(H \rightarrow WW^*) + \Gamma(H \rightarrow ZZ^*) + \Gamma(H \rightarrow \gamma\gamma) + \dots \end{aligned} \quad (2.35)$$

The *branching ratio* (also known as branching fraction) for each decay mode is defined by taking the ratio between the partial decay width for that mode and the total decay width:

$$\text{BR}(H \rightarrow \zeta\zeta') = \frac{\Gamma(H \rightarrow \zeta\zeta')}{\sum_{\zeta\zeta'} \Gamma_{H \rightarrow \zeta\zeta'}} = \frac{\Gamma(H \rightarrow \zeta\zeta')}{\Gamma_{\text{total}}}. \quad (2.36)$$

The partial decay widths can be calculated as a function of the Higgs boson mass parameter. The theoretical prediction for each partial decay width is individually calculated using the HDECAY [13, 14, 15] and PROPHECY4F [16, 17, 18] programs. Once summed together, the prediction for the total width can be obtained, as a function of the Higgs boson mass. This is shown in Figure 2.9, where Γ_H increases as the Higgs mass increases since more decay modes become energetically allowed. Given a Higgs boson with mass ~ 125 GeV, the SM prediction for the total decay width

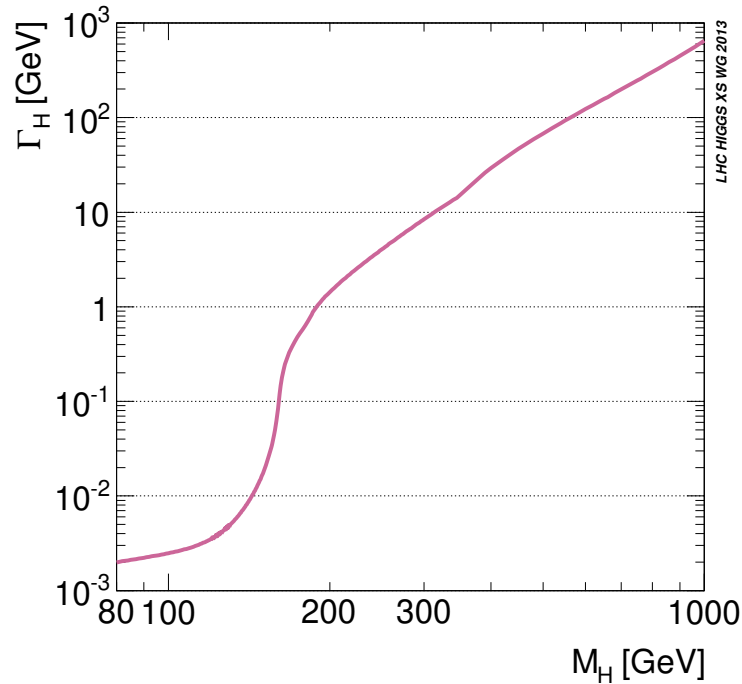


Figure 2.9: Standard Model Higgs boson total decay width, Γ_H , as a function of the Higgs boson mass, m_H [19].

of the Higgs boson is [3]:

$$\Gamma_H^{\text{SM}} = 4.09 \pm 0.16 \text{ MeV}. \quad (2.37)$$

Substituting this SM prediction into equation 2.31 we obtain the expected decay lifetime of the Higgs boson as 1.6×10^{-22} s.

2.2.3 Higgs boson production modes

The leading-order Feynman diagrams corresponding to the dominant Higgs production modes are shown in Figure 2.10. The corresponding production cross sections at $\sqrt{s} = 13$ TeV are shown in Figure 2.11a, as a function of the Higgs boson mass m_H .

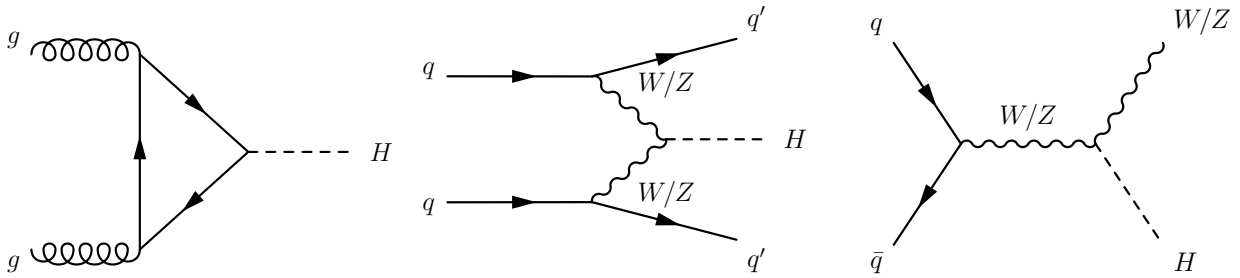


Figure 2.10: Feynman diagrams for the three main production modes of the Higgs boson for pp collisions at $\sqrt{s} = 13$ TeV for a Higgs boson with mass $m_H = 125$ GeV. Gluon-gluon fusion is depicted in the left diagram, vector boson fusion in the centre, and associated production with a vector boson on the right.

The main production mode of the Higgs boson at $\sqrt{13}$ TeV is gluon-gluon fusion (ggF), which corresponds to the dark blue line labelled $pp \rightarrow H$ in Figure 2.11a, which has a cross-section around 48.6 pb. Since the gluon is massless, there is no direct gluon-Higgs coupling, and ggF occurs via the quark loop at lowest order. As the Higgs boson couplings to fermions are proportional to the particle mass, the dominant quark loop contribution in this process is from top quarks given the top is by far the heaviest quark, despite the heavy top mass being kinematically difficult to produce.

Vector boson fusion (VBF) is the second largest production mode, an order of magnitude smaller than ggF; its predicted cross-section is displayed in Figure 2.11a by the line labelled $pp \rightarrow qqH$, which is around 3.8 pb. VBF production occurs when two quarks both emit a W or Z boson, which then combine to produce a Higgs boson. Despite the significantly lower cross-section compared to ggF, VBF induced Higgs boson decays possess several distinguishing features which make its experimental signature comparatively unique, and therefore useful for Higgs boson analyses. This mode is defined by a distinct topology; two highly energetic and *forward* jets, due to the presence of the two quarks in the event. The term *forward* indicates the quark jets are produced along the beam pipe, as opposed to being produced perpendicular to the beam pipe axis in what's classified as the *central* region.

Higgs boson production with an associated vector boson (VH , where $V = W$ or Z), is the third most prevalent Higgs production mode. The production cross-section is shown in Figure 2.11a by the two green lines, one labelled $pp \rightarrow WH$ when the associated vector boson is a W (with a cross-section of 1.4 pb), and the other $pp \rightarrow ZH$ in the case where it's a Z boson (cross-section of 0.8 fb). This mode occurs when two quarks annihilate to produce an off-shell vector boson, V , which then radiates off a Higgs boson. The defining feature of this production mode is the presence of the vector boson in the final state, in addition to the Higgs boson.

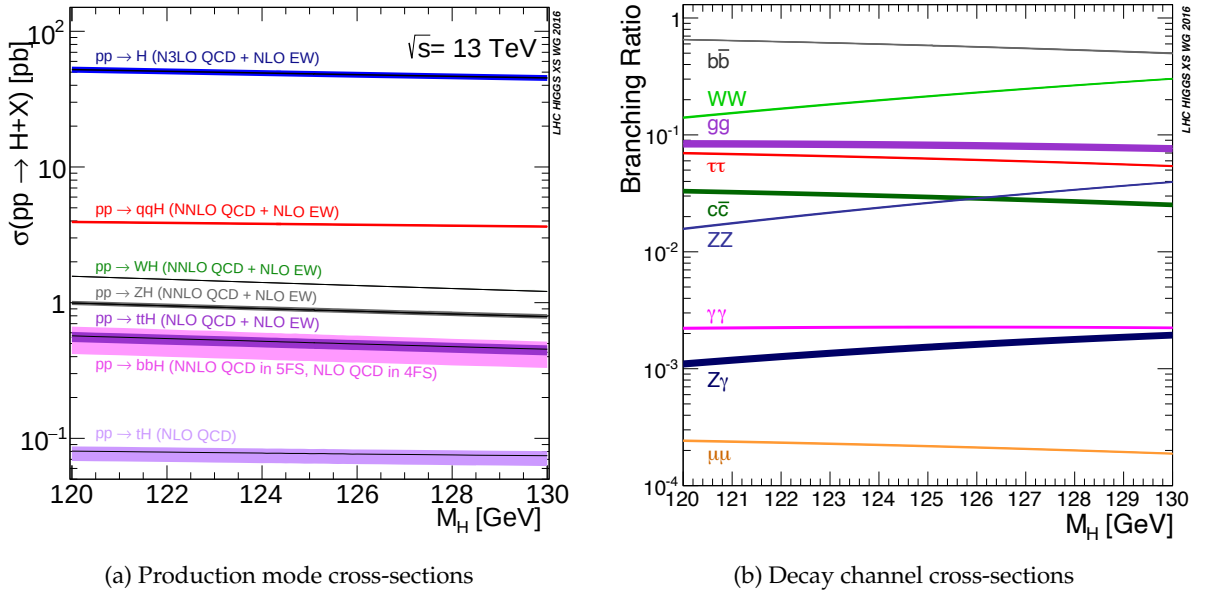


Figure 2.11: Higgs boson production mode (2.11a) and decay channel (2.11b) cross-sections calculated as a function of the Higgs boson mass, m_H , at a centre-of-mass energy of $\sqrt{s} = 13$ TeV [3]. The band represents the magnitude of the theoretical uncertainties.

2.2.4 Higgs boson decay channels

In the SM, the Higgs boson couplings to fermions and gauge bosons are illustrated in Figure 2.12. The strength of the couplings in each case are either directly proportional to the mass of the final state particles in the case of the fermion vertex, or to the mass squared for gauge bosons. The dominant decay modes of the Higgs boson, as a function of the Higgs boson's mass, are displayed in Figure 2.11b. The dominant decay mode is $H \rightarrow b\bar{b}$ with a branching ratio of 58%, followed by $H \rightarrow WW^*$ at 22%. Despite the high $H \rightarrow b\bar{b}$ branching ratio, the measurement of this channel at hadron colliders unfortunately suffers due to the overwhelming presence of QCD multi-jet background events, thus reducing the experimental sensitivity.

For the region where $m_H < 130$ GeV, the dominant Higgs boson decay channel is $H \rightarrow b\bar{b}$, since

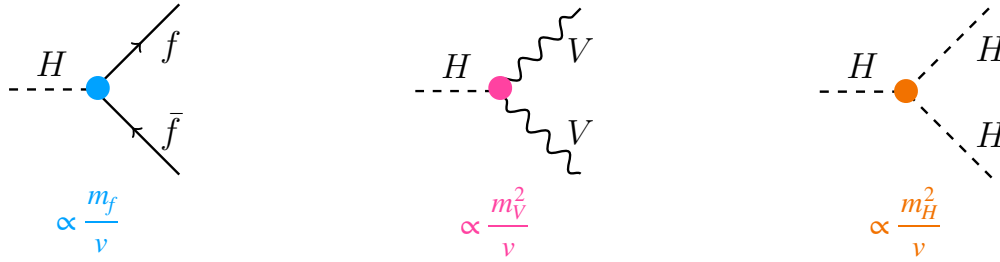


Figure 2.12: SM single Higgs boson couplings. On the left is the Feynman diagram for the Yukawa coupling terms, in the centre is the Higgs to vector boson vertex, and on the right is cubic vertex of a single Higgs coupling to a pair of Higgs bosons.

the Higgs boson couplings are proportional to mass as illustrated in Figure 2.12. The only particles in the SM heavier than the beauty quark is the top quark, however this decay channel is not kinematically viable since $m_H < 2m_t$. In the mass region where $m_H < 130$ GeV, the Higgs boson decay to gauge bosons is only possible if one of the two bosons is produced with a significantly lower energy than its resonant mass value (defined as *off-shell*, meaning off its mass resonance). Alternatively, at higher m_H values $m_H > 160$ GeV the decay channels $H \rightarrow WW$ and $H \rightarrow ZZ$ start to dominate since the Higgs boson has enough energy to produce both bosons *on-shell* (with mass equal to m_V).

$H \rightarrow \gamma\gamma$ decay channel:

One of the sub-dominant Higgs boson decay modes is the decay to a pair of photons, $H \rightarrow \gamma\gamma$, where the expected production cross-section as a function of the Higgs boson mass is shown by the magenta line in Figure 2.11b. This decay channel is of particular significance as it is used for the main physics analysis presented in this thesis. Since the Higgs boson only couples to particles with mass, this specific decay channel occurs at leading order via a loop diagram only; there is no direct Higgs-photon coupling in the SM since the photon is massless. The cross-section for this process is very small (branching ratio $\sim 0.2\%$) due to the loop suppression factor, and in addition the leading order Feynman diagrams, shown in Figure 2.13 destructively interfere. Measuring Higgs boson decays in this channel is especially challenging given the cross-section of the main SM background process, $gg \rightarrow \gamma\gamma$, is around three orders of magnitude larger than the signal cross-section, $gg \rightarrow H \rightarrow \gamma\gamma$.

Despite the small cross-section, this channel is extremely interesting since new particles could appear in the loop which would alter the expected cross-section. Additionally, this particular channel leaves a distinct characteristic experimental signature in the ATLAS detector defined by the presence of two high-energy photons in the event, which allows for favourable discrimination between the signal and background processes. The ATLAS detector maintains an unparalleled

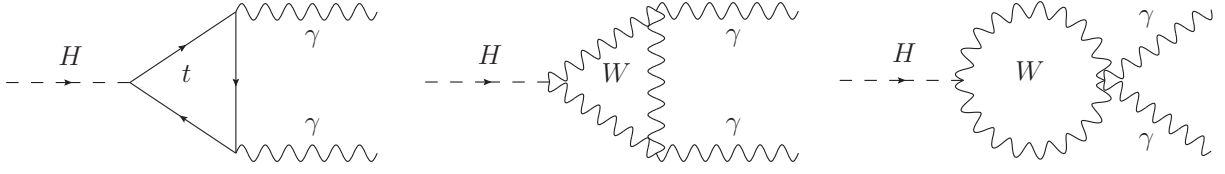


Figure 2.13: Feynman diagrams for the Higgs boson decay to two photons. These diagrams destructively interfere, which contributes to the small branching fraction for this decay mode.

level of photon energy resolution, allowing for an extremely precise determination of the Higgs boson mass. For these reasons, the $H \rightarrow \gamma\gamma$ decay channel is one of the prime channels available to measure properties of the Higgs boson. In fact this channel was one of the two channels used for the Higgs boson discovery measurement; as described in the next section.

2.2.5 Experimental discovery and property measurements

The Higgs boson discovery was made after decades of anticipation given the Higgs boson particle was first predicted to exist by the BEH mechanism. Now more than ten years has passed since the discovery of the Higgs boson by the ATLAS and CMS collaborations in 2012. Sophistication of the utilised analysis techniques, a better understanding of the detector, and the collection of around 10 times the initial dataset has allowed for a more precise Higgs boson mass determination as well as the possibility to measure many additional properties. This section will present the most up-to-date experimental determination of the Higgs boson mass, and the measured production and decay modes.

Mass: There are two main so called *golden channels* used to make the discovery measurement, and to measure the Higgs boson mass: the $H \rightarrow \gamma\gamma$ and the $H \rightarrow ZZ^*$ channels (where the leptonic decay modes of the Z were used). As mentioned in section 2.2.4, despite the small $H \rightarrow \gamma\gamma$ branching ratio, the very clean detector signature of this channel increases its experimental sensitivity. Figure 2.14 shows a side-by-side comparison of the diphoton invariant mass distribution at the time of the Higgs boson discovery, compared to the distribution obtained when analysing 80 fb^{-1} collected during the 2015-2017 data-taking period.

The most recent measurement of the Higgs boson mass in the $\gamma\gamma$ channel is obtained analysing 140 fb^{-1} of data [21]:

$$m_H^{\gamma\gamma} = 125.17 \pm 0.11 \text{ (stat.)} \pm 0.09 \text{ (sys.) GeV} = 125.17 \pm 0.14 \text{ GeV}, \quad (2.38)$$

which is one of the most precise measurements made by the LHC physics programme to date. The dominant source of uncertainty derives from the experimental systematics, specifically related to the energy calibration of the ATLAS electromagnetic calorimeter. Updated photon and

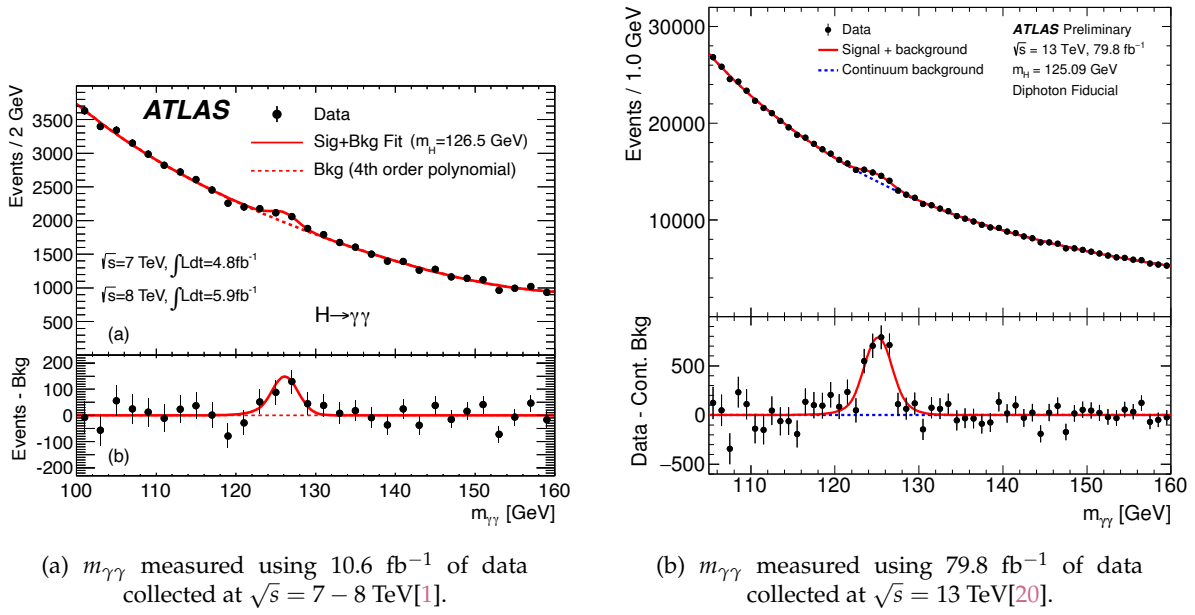


Figure 2.14: Diphoton invariant mass distributions: 2.14a at the time of the Higgs boson discovery in 2012; 2.14b the analysis of the 2015-2017 dataset. The signal peak is visible over the background continuum which has an exponential-like shape, particularly visible in the plot in the bottom panel, which displays background-subtracted data.

electron detector calibrations are expected to significantly reduce this uncertainty for future measurements.

The measurement of the Higgs boson mass via the ZZ^* channel exploits the $Z \rightarrow \ell^+\ell^-$ decay channel of the Z boson, where ℓ refers to an electron or muon. Figure 2.15a shows the invariant mass distribution of the four-lepton system at the time of the Higgs boson discovery, in the $H \rightarrow ZZ^*$ decay channel by the ATLAS experiment; Figure 2.15b instead shows the distribution using data collected between 2015 and 2018. The dominant source of background events to this process is from $pp \rightarrow ZZ^*$ decays, shown in red in Figure 2.15. An obvious improvement in the prominence of the signal peak is evident, shown in blue, with respect to the main background contributions. The current most precise determination of the Higgs boson mass comes from combining the mass measurement obtained from analysing the 2011-2012 dataset with that obtained using the 2015-2018 dataset, in the $H \rightarrow ZZ^*$ decay channel. The measured value is [22]:

$$m_H^{ZZ^*} = 124.94 \pm 0.17 \text{ (stat.)} \pm 0.03 \text{ (sys.) GeV} = 124.94 \pm 0.17 \text{ GeV.} \quad (2.39)$$

The largest uncertainty in this measurement is the statistical component, which corresponds to 85% of the total uncertainty. The collection of more data in the coming years will lead to a further reduction of this uncertainty.

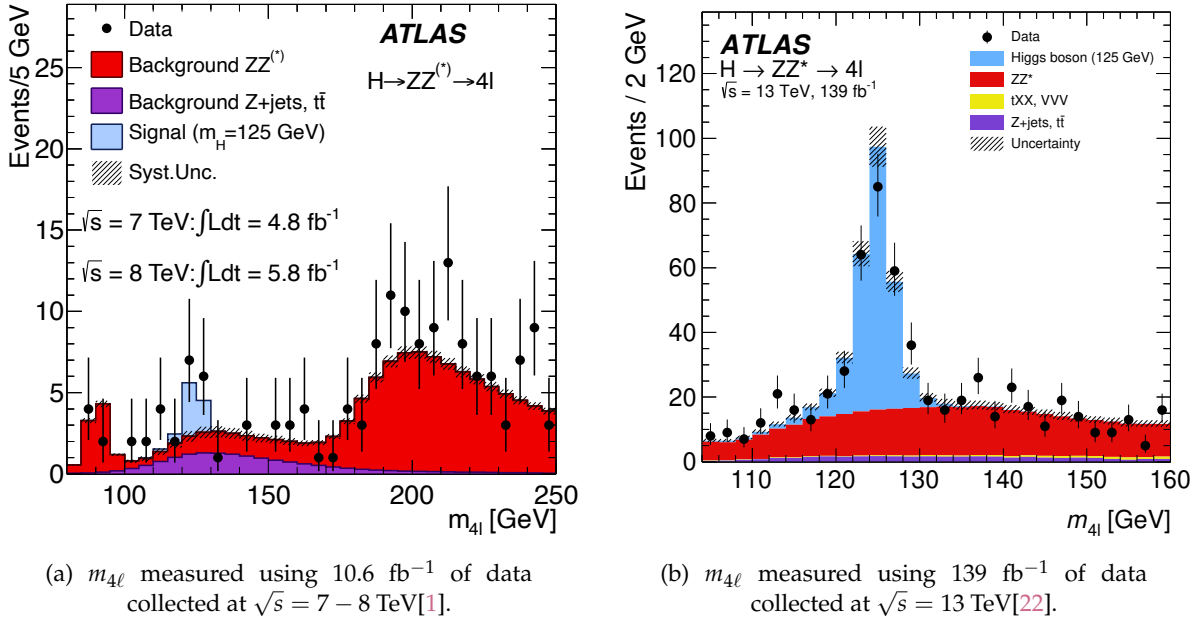


Figure 2.15: Four lepton invariant mass distributions at the time of the Higgs boson discovery in 2012, 2.14a, and following the analysis of the 2015-2018 dataset, 2.14b. The expected signal contribution is shown in blue, while the other colours represent estimations for the background processes.

Width: One Higgs boson property that has yet to be measured in a model-independent way is the Higgs boson total width. This will be the subject of Chapter 3, where the possible measurement techniques will be discussed.

Couplings summary: Measurements of the Higgs boson production and decay modes allow us to verify if the measured Higgs boson agrees with the SM expectations. Deviations between the measured coupling values, and the theoretical predictions could hint at potential sources of new physics. So far, all major production modes of the Higgs boson have been observed with 5σ significance, and an upper limit of $15 \times \text{SM}$ at a 95% confidence level has been placed on the tH production mode. A comparison between the measured cross-section and the SM prediction for each of these production modes is shown in Figure 2.16a. These results are taken from a Higgs boson properties summary paper [2], published by the ATLAS collaboration in *Nature* on the 10 year anniversary of the Higgs boson discovery.

Figure 2.16b compares the measured branching fractions for the main decay channels of the Higgs boson with the SM expectation. So far the $b\bar{b}$, WW^* , $\tau^+\tau^-$, ZZ^* and $\gamma\gamma$ decay channels have all been measured with more than 5σ significance, using a variety of production modes. All measured branching fraction values are consistent with the SM predictions. To search for potential deviations from the SM predictions, an effective field theory (EFT) approach is typically used to search for new physics well above the currently accessible energy reach with the LHC. Although

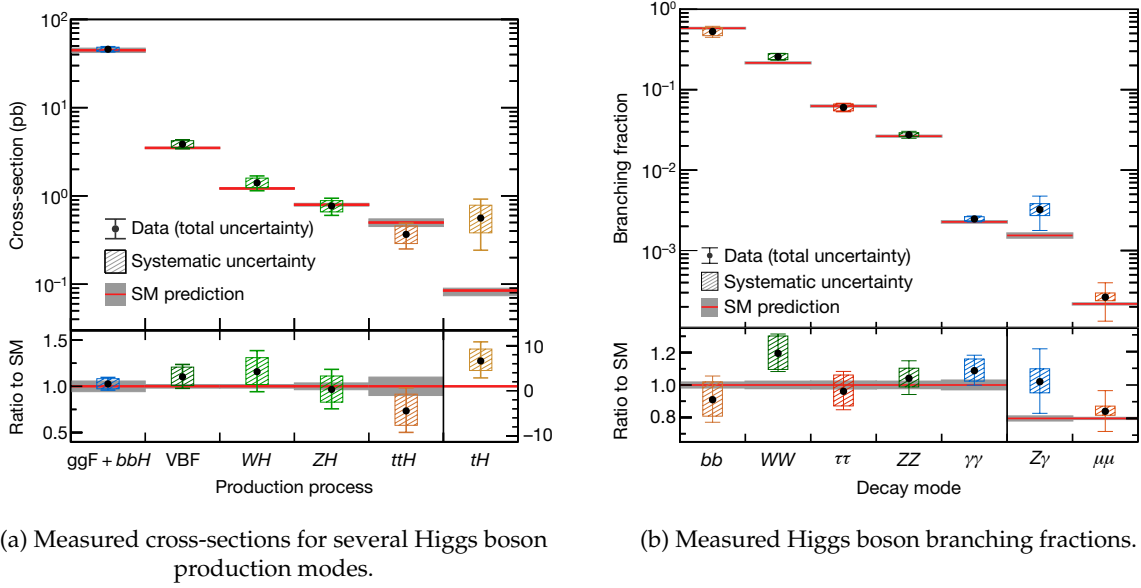


Figure 2.16: Comparison between measured Higgs boson properties and the SM prediction [2].

discussion of the SM EFT is beyond the scope of this thesis, the following references provide up-to-date summaries of the latest EFT and combined Higgs boson measurements: [23, 24, 25].

Immense progress has transpired over the last 10 years in our understanding of the Higgs boson particle; as we now move to a precision era, there are still Higgs couplings and properties which have not yet been measured. Decays to second (or first) generation fermions have not been observed yet; the $H \rightarrow c\bar{c}$ search allowed for an observed upper limit to be placed on $\sigma \times BR(H \rightarrow c\bar{c})$ of 26 times the SM prediction [26]. There is a strong hint also for Higgs boson decays to second generation leptons, via $H \rightarrow \mu^+\mu^-$ decays where an upper limit of 2.2 times the SM prediction was placed on $\sigma \times BR(H \rightarrow \mu^+\mu^-)$ [27]. Recent evidence has been found of rare Higgs decays such as the $H \rightarrow Z\gamma$ decays [28], and the collection of more data in the coming years will allow for rarer decays such as this one to be measured, if they exist. The Higgs boson decay width, Γ_H , has also not been precisely determined in a model-independent way which, as mentioned in section 2.2.2, is linked to the sum of the allowed Higgs boson decay channels and is therefore of significant importance for our understanding of the Higgs boson. A detailed description of the possible Γ_H measurement techniques will be outlined in following chapter.

3 | Determination of the Higgs boson width

This chapter presents an overview of the possible techniques to measure the Higgs boson total decay width, the benefits and limitations of each, and the relevant most-recent experimental results.

The Higgs boson width, whose value is predicted by the SM once the Higgs boson mass is determined, is an important property to measure as it is a useful probe for beyond the SM physics. As was introduced in section 2.2.2, the predicted width of the Higgs boson resonance is very narrow, relative to the measured value of the Higgs boson mass. Should there be a new non-SM particle which couples to the Higgs boson, this would increase the number of Higgs boson decay channels, corresponding to a shorter decay lifetime ($\equiv$ larger Higgs boson width as per equation 2.31). This would manifest as a deviation in the measured Higgs boson width with respect to the theoretically predicted value, expressed as:

$$\Gamma = \Gamma_{\text{SM}} + \Delta\Gamma_{\text{BSM}}, \quad (3.1)$$

where $\Delta\Gamma_{\text{BSM}}$ parametrises any deviation from the theoretically predicted value. The sensitivity to BSM effects is inextricably linked to the accuracy with which we can measure Γ , motivating the need for a precise Higgs boson width measurement. Experimental determination of this property is therefore an invaluable tool to probe the nature of the Higgs boson, and the SM in general, given this parameter is sensitive to effects coming from Higgs boson decay channels which we might not be able to directly measure with the ATLAS detector. An example of where the determination of the decay width has been useful in the past was at the Large Electron-Positron (LEP) collider whereby the invariant mass distribution of the Z-boson was studied to extract the number of light neutrino species. The final result of this measurement can be seen in Figure 3.1, where the large dependence of the number of light neutrino flavours, N_ν , is evident. The expected distribution given two, three, and four neutrino flavours is displayed by the three labelled curves.

Techniques for measuring the Higgs boson width can be broadly grouped into two categories: direct and indirect methods, depending on whether the measurement strategy targets use of the resonance signal peak in the distribution of the parameter of interest, or not. The main direct

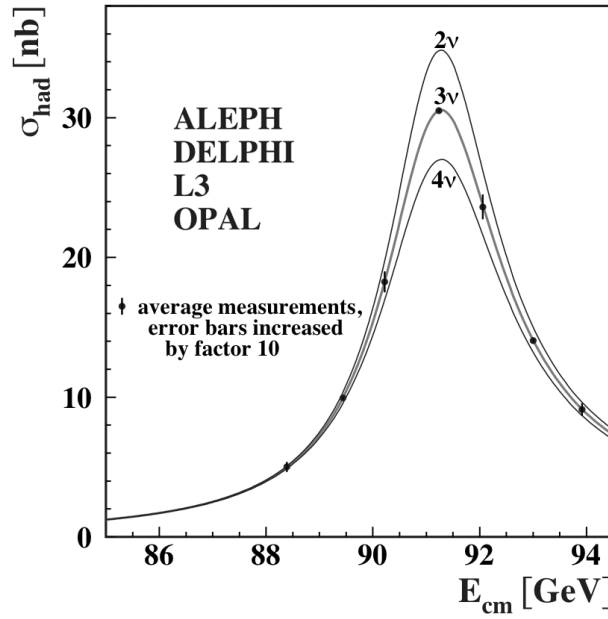


Figure 3.1: Hadron production cross-section measurements as a function of the LEP centre-of-mass energy, near the Z boson resonance [29]. The data points are combined measurements from the ALEPH, DELPHI, L3, and OPAL experiments and are consistent with $N_\nu = 3$, corresponding to three light neutrino flavours. The predicted lineshape given the $N_\nu = 2, 3$ and 4 hypotheses are displayed. All measurement uncertainties are scaled up by a factor of 10 for visibility.

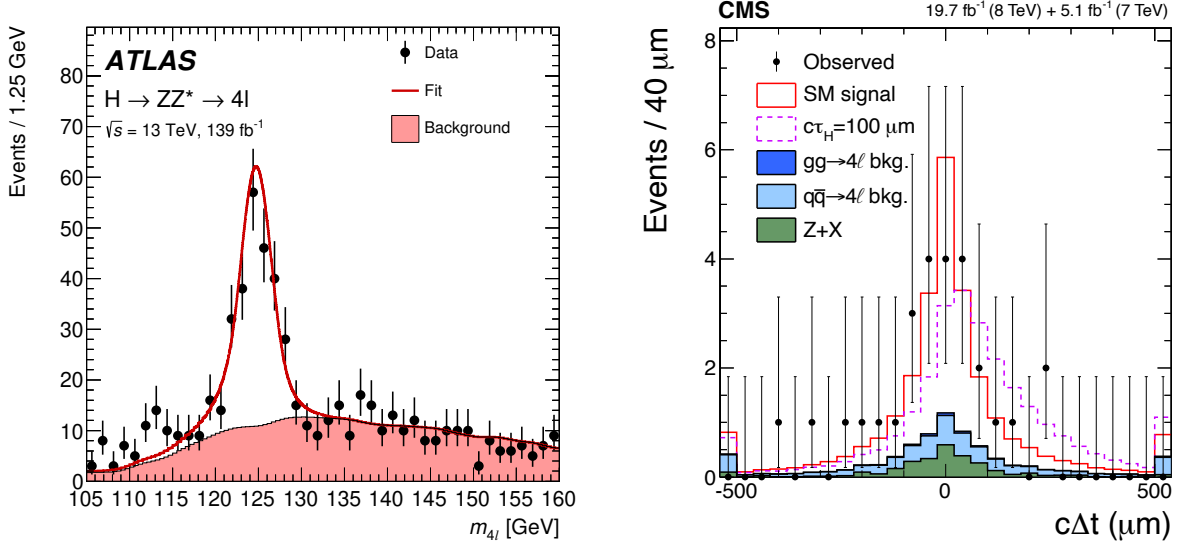
methods will be outlined in section 3.1, whilst the remainder of the chapter is dedicated to indirect methods.

3.1 Direct methods to measure the Higgs boson width

Perhaps the most intuitive direct method involves studying in detail the invariant mass distribution of the Higgs boson decay products, correcting for the experimental resolution, and subsequently extracting the width of the Breit-Wigner resonance. This is possible since the width of this peak corresponds to the total decay width of the unstable particle by definition, though is convoluted with the detector resolution of the final state particles. This was the technique used to determine the width of the W boson, $\Gamma_W = 2.085 \pm 0.042$ GeV [6, 30], which is orders of magnitude larger than that of the predicted SM value of the Higgs boson width, $\Gamma_H^{\text{SM}} = 4.09$ MeV. Using this method to determine the Higgs boson width is limited by the experimental resolution of the ATLAS detector which is on the order of 1 - 3 GeV¹. The most recent ATLAS analysis exploiting this technique uses the observed resonance in the invariant mass distribution in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel, and places a 95% confidence level upper limit on Γ_H of 2.6 GeV [31], which is three orders of magnitude larger than the theoretical expectation. An example of the ZZ invariant mass distribution given 139 fb⁻¹ of data is shown in Figure 3.2a. CMS have recently

¹Variations in the mass resolution derive from their dependence on the chosen Higgs boson decay channel, and the considered kinematic region.

published their updated analysis using this direct measurement technique, where they report an observed upper limit of $\Gamma < 330$ MeV at 95% C.L. [32], where 138 fb^{-1} of data at $\sqrt{s} = 13$ TeV has been used to perform this analysis.



(a) Four lepton invariant mass distribution showing the Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4l$ decay channel, on top of the ZZ background [22]. The width of the signal peak ($\sim 1 - 2$ GeV) is evidently much larger than the expected intrinsic Higgs boson width value of 4.1 MeV.

(b) The $c\Delta t$ distribution used to place an upper limit of $\tau_H < 1.9 \times 10^{-13}$ s on the lifetime of the Higgs boson at the 95% confidence level [33]. The predicted SM signal is indicated by the red line; a possible alternate non-SM signal with $c\tau_H = 100 \mu\text{m}$ is shown by the dashed purple line.

Figure 3.2: Direct measurement techniques used to constrain the Higgs boson width: 3.2a using the width of the m_{ZZ} invariant distribution mass peak; 3.2b taking the average of the measured Higgs boson lifetime, $c\Delta t$.

A second technique to determine the Higgs boson width is through measuring the Higgs boson decay lifetime. Making use of the equation 2.31 relation, the average lifetime for Higgs boson candidates, $\langle \Delta t \rangle$, is defined as:

$$\langle \Delta t \rangle = \tau_H \equiv \frac{1}{\Gamma_H}, \quad (3.2)$$

where Δt defines the lifetime for an individual Higgs boson candidate. Since the decay lifetime and the total decay width are directly (inversely) related, a measurement of the lifetime is a *direct* determination of the Higgs boson width.

The Higgs boson lifetime can be derived through measuring the particle's flight distance within the detector volume. The spread of measured decay lifetimes depends on the invariant mass of the final state particles, and the transverse momentum vector of the reconstructed Higgs boson. The expected lifetime is $\tau_H \approx 48 \text{ fm}/c$. An analysis of this nature was undertaken by the CMS experiment, using data collected during Run 1. The distribution of measured flight distances, $c\Delta t$,

is shown in Figure 3.2b, where the expected SM signal distribution is shown in red. The resulting upper limit on the decay lifetime is $\tau_H < 1.9 \times 10^{-13} \text{ s} = 190 \text{ fs}$ at the 95% confidence level, which is nine orders of magnitude larger than the SM expectation value $\tau_H^{\text{SM}} = 1.6 \times 10^{-22} \text{ s}$ [33]. The obtained upper bound on the Higgs boson lifetime translates into a lower limit on the total decay width, $\Gamma_H > 3.5 \times 10^{-9} \text{ MeV}$. The constraining power of this technique will always be limited by the fact that the theoretically predicted flight distance of the Higgs boson is much too short to be measurable with the current $\mathcal{O}(10 \mu\text{m})$ displacement resolution of the ATLAS or CMS detectors. This causes a lack of experimental sensitivity, and thus a measurement of the Higgs boson lifetime has not been repeated since.

As neither of these direct methods are able to reach a precision anywhere near the expected Higgs boson width, it was long thought that the experimental verification of the Higgs boson decay width would be forever out of reach. However in 2013, two independent novel techniques were proposed [4, 34] that could allow for experimental reach through indirect means. The first so-called *off-shell* method studies the ratio of the production cross-sections of Higgs bosons in the off-shell and on-shell invariant mass regions using $H^* \rightarrow ZZ$ or $H^* \rightarrow WW$ decays. The second method known as *interferometry* exploits shape and yield effects on the Higgs boson invariant mass distribution due to the presence of interference contributions, and have a sizeable impact in the $H \rightarrow \gamma\gamma$ decay channel specifically. Interference also occurs in the $H \rightarrow ZZ^*$ channel however the impact on the measured mass value is numerically small, $< 10 \text{ MeV}$ [35], providing Γ_H is somewhat close to the SM expectation. As will be discussed in section 3.3, the effects in the $H \rightarrow \gamma\gamma$ channel are expected to be much larger. The off-shell and interferometry methods will be described in section 3.2 and 3.3 respectively, where each will firstly be conceptually outlined and theoretically motivated, followed by a discussion of the most recent experimental results.

3.2 The off-shell method using $H^* \rightarrow ZZ$ decays

The off-shell method is used to determine the Higgs boson width using the $H^* \rightarrow ZZ$ and $H^* \rightarrow WW$ decay channels. The section will focus on outlining the off-shell method using the $H^* \rightarrow ZZ$ channel only, the main reason being that this is the most sensitive decay channel thanks to the 4-lepton final state which is experimentally very clean compared to the alternatives, which have neutrinos (so missing energy) present, and conceptually the method works the same in both channels. Additionally, although not included in this thesis, I also contributed to the Higgs boson width measurement in the $H^* \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ decay channel.

The Feynman diagram for the $gg \rightarrow H^* \rightarrow ZZ$ process is shown in Figure 3.3a, where the ggF production mode of the Higgs boson occurs at leading order via either a fermion or W boson loop. Since the Higgs boson coupling is proportional to mass, the fermion loops are usually comprised of top (or bottom) quarks. An effective coupling can be obtained from the quark loop by treating

it as a single vertex, with strength g_{ggH} . The coupling on the decay of the Higgs boson instead is denoted g_{HZZ} . The main SM background to this process are $gg \rightarrow ZZ$ decays, shown in Figure 3.3b, which has a cross-section roughly 6 times larger than the $H^* \rightarrow ZZ$ process.

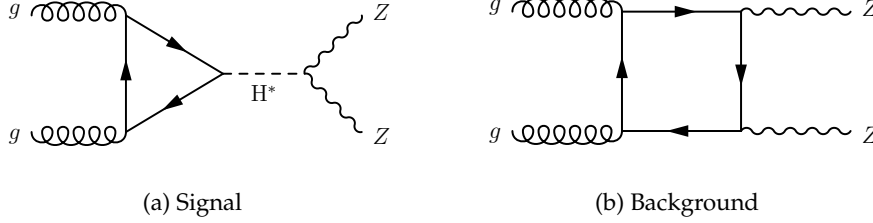


Figure 3.3: Feynman diagrams for the (3.3a) $gg \rightarrow H^* \rightarrow ZZ$ non-resonant signal process, and (3.3a) the $gg \rightarrow ZZ$ background process. The fermion loop for the Higgs boson production is dominated by top and bottom quarks, while for the background case the loop is predominantly light quarks.

Structure of the Higgs boson resonance:

The cross-section for the full $gg \rightarrow H \rightarrow ZZ$ process can be expressed as:

$$\sigma(gg \rightarrow H \rightarrow ZZ) \propto \frac{g_{ggH}^2 \cdot g_{HZZ}^2}{(s - m_H^2)^2 + m_H^2 \Gamma_H^2}, \quad (3.3)$$

where s is the centre-of-mass energy squared, and g_{ggH} and g_{HZZ} represent the g -Higgs and Higgs- Z boson coupling vertices respectively. This notation is explicitly for the ggF production mode however the principle is the same for the other modes. When looking at the invariant mass distribution of the Higgs boson resonance, specifically (though not generally exclusively) in the four lepton decay channel (then $m_H \equiv m_{4\ell}$), we see that it can be split into two regions: the *on-shell* region where m_H is close to the peak ($s \sim m_H^2$), and an *off-shell* region where $s \gg m_H^2$. The on-shell region is characterised by the resonance peak, deriving from the propagator term $\propto 1 / [(s - m_H^2)^2 + m_H^2 \Gamma_H^2]$. These two regions are defined in the Figure 3.4 illustration of the $m_{4\ell}$ invariant mass distribution.

To understand why the invariant mass distribution has such extended (and observable) tails, given narrowness of the resonance peak due to the short lifetime, we must look at the properties of this particular Higgs boson decay as there are some unique kinematic features. The off-shell region corresponds to $\mathcal{O}(15\%)$ of the total Higgs boson cross-section, which is due to two enhancement effects. In the region where $m_H \geq 2m_Z \sim 180$ GeV, an increase in kinematic phasespace occurs due to the on-shell production of both Z bosons becoming energetically feasible. Before this threshold is reached, an on-shell Higgs boson does not have sufficient energy to produce two on-shell Z bosons (hence why one is typically denoted Z^*), and thus is produced with mass $m_{Z^*} < 91$ GeV. Additionally, there is a $t\bar{t}$ threshold at $m_H \geq 2m_t \sim 350$ GeV deriving from the top

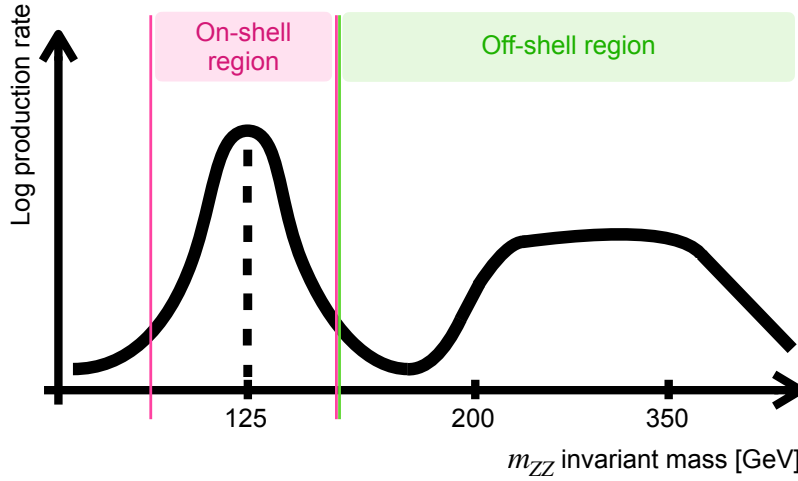


Figure 3.4: Illustration depicting the two regions of the $m_{4\ell}$ invariant mass distribution. The on-shell region, shown in pink, is defined within a small region around the Higgs boson mass. The off-shell region instead is where the Higgs boson is not produced with mass significantly exceeding its resonance value: $m_{4\ell} \geq 2m_Z \sim 180$ GeV, indicated in green. The relative production rates of each region are not to scale; the off-shell cross-section, $\sigma_{\text{off-shell}}$ is roughly $\mathcal{O}(15\%)$ of the total Higgs boson cross-section. Note the production cross-section is not to scale.

quarks in the gluon-gluon fusion loop which leads to an additional enhancement since the top quarks can be produced on-shell, removing the suppression factor associated with the off-shell production requirement in the $m_H < 350$ GeV regime. These two thresholds enhance the off-shell cross-section, which is pictorially shown in Figure 3.4, and are also true for $H^* \rightarrow WW$ decays. In the off-shell region, the $H^* \rightarrow WW$ and $H^* \rightarrow ZZ$ decays have the two largest branching ratios, and in fact are the only two decay channels with a branching ratio larger than 0.01 (see Figure 2.11b). The decline in off-shell production rate above the 350 GeV threshold is due to the falling parton densities at high energies.

Cross-sections in the on-shell and off-shell regions:

Taking $s \rightarrow m_H^2$ for the on-shell region, the cross-section defined in equation 3.3 can be simplified to:

$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \propto \left(\frac{g_{ggH} \cdot g_{HZZ}}{m_H \Gamma_H} \right)^2. \quad (3.4)$$

A dependence on the Higgs boson width, Γ_H , is evident in this expression. A measurement solely of the on-shell production cross-section however cannot be used to measure the width, since it is inextricably linked to the couplings. Using this expression alone, there is no way to disentangle the Γ_H and coupling $g_{ggH} \cdot g_{HZZ}$ terms.

Consider now the off-shell region, where $s \gg m_H^2$, then the production cross-section from equation 3.3 becomes:

$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \propto \left(\frac{g_{ggH} \cdot g_{HZZ}}{m_{ZZ}^2 - m_H^2} \right)^2, \quad (3.5)$$

which does not depend on the Higgs boson width. It is clear that if you took the ratio between these two cross-sections $\sigma^{\text{off-shell}} / \sigma^{\text{on-shell}}$, the couplings would cancel out and allow for the width determination. This would only be valid if the effective g_{ggH} and g_{HZZ} couplings are equivalent in the two considered energy regimes. We know already from the SM (section 2.1.2) that this is not the case since the strong (and electroweak to a lesser extent) coupling constants depend on the energy scale at which they are evaluated. To deal with such a dependence, the coupling terms are parametrised in terms of coupling modifiers, κ , by taking the coupling g_X normalised by the SM expectation, g_X^{SM} , such that $\kappa_X = g_X / g_X^{\text{SM}}$ for some Higgs coupling X . We can subsequently normalise the cross-sections by the SM expectation, which results in a cancellation of the couplings g_X , leaving only the coupling modifiers and other terms. This defines the *signal strength* parameter, μ , which for the on-shell region is given as:

$$\mu_{\text{on-shell}} = \frac{\sigma_{pp \rightarrow H \rightarrow ZZ}}{\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{SM}}} \bigg|_{\text{on-shell}} = \frac{\kappa_{g, \text{on-shell}}^2 \cdot \kappa_{Z, \text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}, \quad (3.6)$$

and in the case of the off-shell region instead yields:

$$\mu_{\text{off-shell}} = \frac{\sigma_{pp \rightarrow H \rightarrow ZZ}}{\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{SM}}} \bigg|_{\text{off-shell}} = \kappa_{g, \text{off-shell}}^2 \cdot \kappa_{Z, \text{off-shell}}^2. \quad (3.7)$$

The technique defined in [34] proposes to take the ratio between the signal strengths in the on-shell and off-shell regions, in order to remove the dependence on the coupling terms, and thus be sensitive to the Higgs boson width. In doing so, the Higgs boson width is parametrised in terms of the signal strengths as:

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}, \quad (3.8)$$

Note that the cancellation of coupling modifiers is only possible if $\kappa_{g, \text{off-shell}} = \kappa_{g, \text{on-shell}}$ and $\kappa_{Z, \text{off-shell}} = \kappa_{Z, \text{on-shell}}$. These requirements are equivalent to assuming that the ratio of on-shell and off-shell couplings is exactly that predicted by the SM; a restriction is being placed on the values to be SM-like and thus becoming insensitive to relevant BSM effects. There are several theories in fact which predict the existence of BSM physics that would alter the couplings in the off-shell region only, for example through the existence of additional Higgs boson states [36]. Since experimental LHC measurements thus far indicate consistency with the SM predicted cross-sections, such an assumption seems generally reasonable, though it is important to keep this detail in mind since it is intrinsically tied to the off-shell method for determining the Higgs boson width.

Measuring the signal strengths in the on-shell and off-shell region and taking the ratio is the crux of the off-shell method, which has been used as the analysis strategy by the ATLAS and CMS experiments in order to measure Γ_H . To undertake such a measurement, the cross-section of events in the off-shell region must be sufficiently high to be observable. There are two sources of events in this region: one being the aforementioned off-shell production of the Higgs boson, the second being the interference between the signal $gg \rightarrow H^* \rightarrow ZZ$ and background $gg \rightarrow ZZ$ processes displayed in Figure 3.3. Since both processes have the same initial and final states, quantum interference occurs between these two processes, commonly denoted $gg \rightarrow (H^* \rightarrow)ZZ$. This interference exists across the entire energy range considered, however is numerically irrelevant in the on-shell peak region as the $gg \rightarrow ZZ$ process is suppressed there and so can be ignored to good approximation in this region [35, 37]. In the off-shell region however the presence of such interference results in a deficit of continuum ZZ background events, which overall benefits the sensitivity of the analysis.

The cross-section for the combined signal (S), background (B) and interference (I) contributions is given by:

$$\sigma_{gg \rightarrow (H \rightarrow) ZZ} = |\sqrt{\mu_{\text{off-shell}}} \mathcal{M}_{\text{sig}} + \mathcal{M}_{\text{bkg}}|^2 \quad (3.9)$$

$$= \mu_{\text{off-shell}} S + \sqrt{\mu_{\text{off-shell}}} I + B, \quad (3.10)$$

where by definition the signal term scales by the signal strength. Notice in equation 3.10 that the interference term scales as a function of $\sqrt{\mu_{\text{off-shell}}}$. In the SM scenario ($\mu_{\text{off-shell}} = 1$), the contribution to the cross-section due to the interference is larger compared to that of the signal, in the off-shell region. This is beneficial since it allows the off-shell signal strength to be measured via the interference, rather than relying solely on the resonant signal. Section 3.2.1 outlines the latest experimental results of the Higgs boson width determination using the off-shell method, where the parametrisation defined in equation 3.10 is used to measure the invariant mass distribution of $H \rightarrow ZZ$ events, so to extract $\mu_{\text{off-shell}}$, and subsequently Γ_H .

3.2.1 Experimental results

In 2023 the ATLAS collaboration published a measurement of the Higgs boson width using the aforementioned off-shell method, following the analysis of the 139 fb^{-1} collected between 2015 and 2018, at $\sqrt{s} = 13 \text{ TeV}$. This analysis targets Higgs boson decays to a pair of Z bosons, where the final state consists of either 4ℓ , where $\ell = e, \mu$, or $2\ell 2\nu$. These two final states are analysed independently, before combining to produce the final result. In the 4ℓ final state, the invariant mass of the four lepton final state, $m_{4\ell}$, is used to define the likelihood function. This is possible because all final state particles are reconstructed by the ATLAS detector. The $2\ell 2\nu$ final state instead contains missing transverse energy in the final state due to the neutrinos escaping detection. The analysis of $2\ell 2\nu$ events instead uses the invariant mass of the ZZ system in the

transverse plane, m_T^{ZZ} . In both analyses, three signal regions are defined: a ggF-enriched region, a more VBF-enriched region, and a mixed region; the main background comes from irreducible $q\bar{q} \rightarrow ZZ$ events. The $2\ell 2\nu$ channel has a larger cross-section than the 4ℓ final state though suffers from signal regions with increased contamination from background events compared to the 4ℓ channel. The inclusive invariant mass distributions are shown in Figure 3.5 where the observed data is compared to the SM prediction (using MC simulated events); Figure 3.5a corresponds to the $m_{4\ell}$ distribution in the 4ℓ channel, while Figure 3.5b displays the m_T^{ZZ} distribution used for the $2\ell 2\nu$ analysis. The transverse mass is roughly defined by summing in quadrature the mass of the Z boson and the transverse momentum of the $\ell\ell$, whilst accounting for the missing transverse energy.

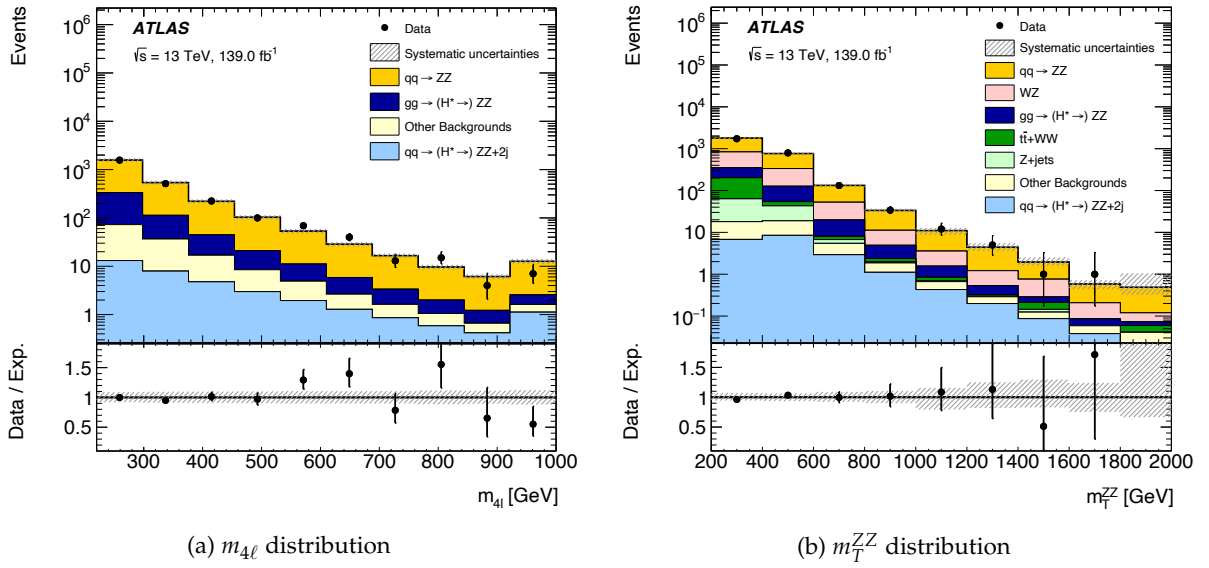
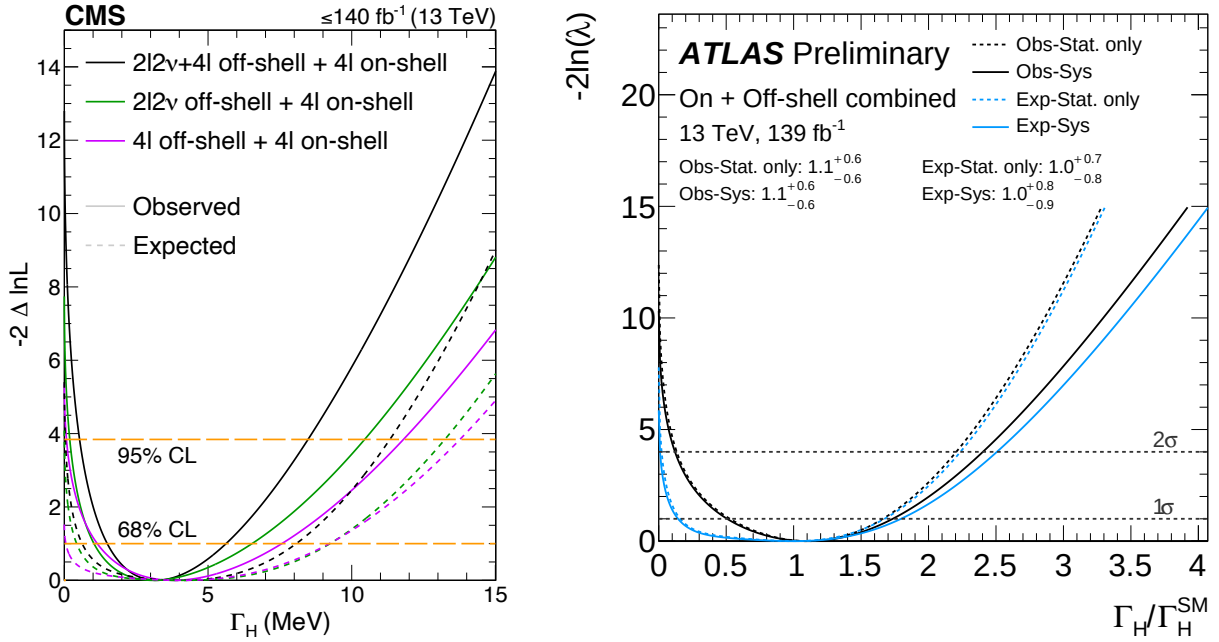


Figure 3.5: Comparisons between the observed data and the prediction for (3.5a) the $m_{4\ell}$ distribution used in the analysis of the 4ℓ final state, and (3.5b) the m_T^{ZZ} distribution used in the $2\ell 2\nu$ final state off-shell analysis [38].

The measured total decay width was found to be $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV [38], which is consistent with the result published by CMS. The measured Higgs boson width is obtained by performing a profile likelihood scan over Γ_H , shown in Figure 3.6b, where the uncertainties on Γ_H are defined by the $\pm 1\sigma$ values.

The CMS collaboration also published a measurement of the Higgs boson width in 2021 using the off-shell method. This analysis makes use of 138 fb^{-1} of data collected at $\sqrt{s} = 13 \text{ TeV}$ between 2015 and 2018, exploiting $H \rightarrow ZZ$ decays (both 4ℓ and $2\ell 2\nu$ final states being included). The profile likelihood scan performed over $\Gamma_H / \Gamma_H^{\text{SM}}$ used to extract this result is shown in Figure 3.6a, where the Higgs boson width is extracted as $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV [39].



(a) The Higgs boson total decay width measured by the CMS collaboration is $\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$ [39].

(b) The Higgs boson total decay width measured by the ATLAS collaboration is $\Gamma_H = 4.5^{+3.3}_{-2.5} \text{ MeV}$ [38].

Figure 3.6: Profile likelihood scans over Γ_H , from the CMS (3.6a) and ATLAS (3.6b) analyses to measure the Higgs boson total decay width, Γ_H . Both analyses use $\sim 140 \text{ fb}^{-1}$ of data collected at $\sqrt{s} = 13 \text{ TeV}$, to analyse $H \rightarrow ZZ$ decays in the on-shell and off-shell regions.

These two independent results correspond to the most precise determination of the Higgs boson width thus far. Despite the precision achieved, the model-dependent nature of the on-shell and off-shell coupling assumptions render the desire for a more model-independent avenue for the width determination. One such proposed technique will be described in section 3.3.

3.3 Interferometry using the $H \rightarrow \gamma\gamma$ channel

Quantum interference occurs between any transition processes with the same initial and final state. The presence of such interference may lead to measurable effects, as is the case in the $gg \rightarrow H \rightarrow \gamma\gamma$ decay channel, which was initially proposed in 2012 by S. Martin [40], and in 2013 by L. Dixon and Y. Li [4]. Determining the Higgs boson decay width by exploiting such interference effects is the main subject of this thesis. This section provides a theoretical introduction to this technique and the possible theoretically-motivated analysis strategies.

3.3.1 $gg \rightarrow (H \rightarrow) \gamma\gamma$ interference at the LHC

The dominant SM Higgs boson production mode at the LHC is via gluon-gluon fusion, as described in section 2.2.3 of Chapter 2. Since both the resonant Higgs boson signal process, $gg \rightarrow H \rightarrow \gamma\gamma$, and the continuum QCD background, $gg \rightarrow \gamma\gamma$, have two gluons in the initial state and two

photons in the final state, this leads to interference. The presence of such interference is commonly denoted $gg \rightarrow (H \rightarrow)\gamma\gamma$ which is a way to indicate all three of the signal, background and interference processes simultaneously. Representative Feynman diagrams for the gg -interference contributions at LO and NLO are shown in Figure 3.7, up to order α_s^3 .

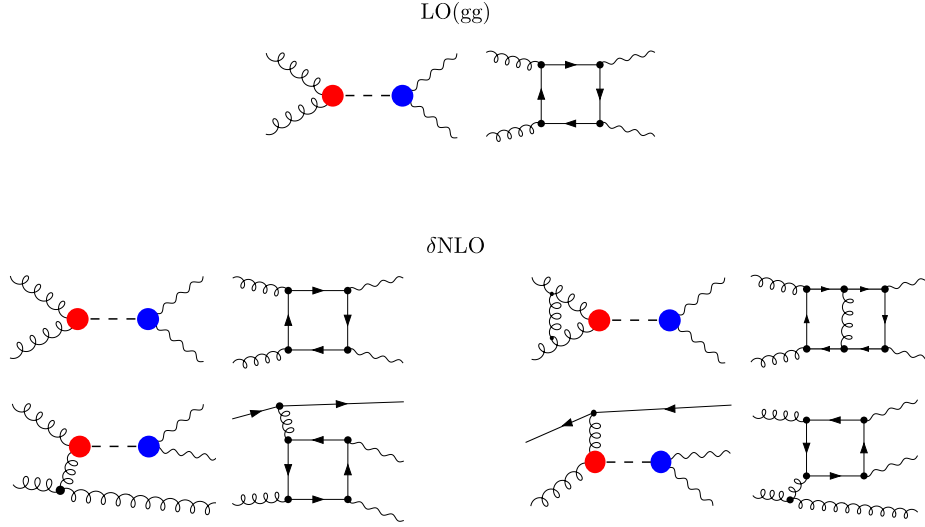


Figure 3.7: Feynman diagrams depicting the gg -interference at LO, as well as NLO corrections, occurring between the $gg \rightarrow H \rightarrow \gamma\gamma$ signal and QCD $gg \rightarrow \gamma\gamma$ background processes, up to order α_s^3 [41]. In each pair of diagrams, the signal process is drawn on the left, whilst the background is on the right. The red dot indicates the effective vertex considered for the Higgs boson production, whilst the blue dot denotes the effective vertex of the Higgs boson decay via the W boson or heavy quark loops.

The matrix element for the $gg \rightarrow \gamma\gamma$ process is defined by:

$$\mathcal{M}_{gg \rightarrow \gamma\gamma} = \frac{\mathcal{M}_{\text{sig}}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H} + \mathcal{M}_{\text{bkg}}, \quad (3.11)$$

where the Higgs boson propagator has been explicitly factored out, and the invariant mass for the two photons is denoted $m_{\gamma\gamma}$. The notation used here and in this section largely follows that in [41]. The diphoton invariant mass distribution is what we're interested in from an experimental perspective, hence it's useful to take the square of the matrix element defined in equation 3.11, which produces

$$|\mathcal{M}_{gg \rightarrow \gamma\gamma}|^2 = \frac{|\mathcal{M}_{\text{sig}}|^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} + |\mathcal{M}_{\text{bkg}}|^2 + 2\text{Re} \left(\frac{\mathcal{M}_{\text{sig}}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_H} + \mathcal{M}_{\text{bkg}}^\dagger \right). \quad (3.12)$$

Denoting the first two terms for simplicity as $|S|^2$ and $|B|^2$ respectively, we can take a closer look at the composition of the final interference term. It is useful to define the real and imaginary

components separately for each of the signal and background matrix elements, i.e.:

$$\mathcal{M}_{\text{sig, bkg}} = \text{Re}\mathcal{M}_{\text{sig, bkg}} + i\text{Im}\mathcal{M}_{\text{sig, bkg}}. \quad (3.13)$$

In doing so, equation 3.12 becomes

$$\begin{aligned} |\mathcal{M}_{gg \rightarrow \gamma\gamma}|^2 &= |S|^2 + |B|^2 \\ &+ \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} [(m_{\gamma\gamma}^2 - m_H^2) \cdot (\text{Re}\mathcal{M}_{\text{bkg}}\text{Re}\mathcal{M}_{\text{sig}} + \text{Im}\mathcal{M}_{\text{bkg}}\text{Im}\mathcal{M}_{\text{sig}})] \\ &+ \frac{2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2} [\Gamma_H m_H \cdot (\text{Re}\mathcal{M}_{\text{bkg}}\text{Im}\mathcal{M}_{\text{sig}} - \text{Im}\mathcal{M}_{\text{bkg}}\text{Re}\mathcal{M}_{\text{sig}})]. \end{aligned} \quad (3.14)$$

The third term of equation 3.14 corresponds to the so-called *real*-part of the interference, where we define $\text{Re}I = \text{Re}\mathcal{M}_{\text{bkg}}\text{Re}\mathcal{M}_{\text{sig}} + \text{Im}\mathcal{M}_{\text{bkg}}\text{Im}\mathcal{M}_{\text{sig}}$, and the fourth term is the *imaginary*-part of the interference, where we denote $\text{Im}I = \text{Re}\mathcal{M}_{\text{bkg}}\text{Im}\mathcal{M}_{\text{sig}} - \text{Im}\mathcal{M}_{\text{bkg}}\text{Re}\mathcal{M}_{\text{sig}}$. Note these labels do not at all correspond to whether the terms are for example physically observable in the invariant mass distribution, but simply derive from which component of the signal and background matrix elements they originated.

The real and imaginary interference components affect the diphoton invariant mass distribution in distinct ways given they're difference dependencies on $m_{\gamma\gamma}$. The real-part is antisymmetric around the peak in the invariant mass, and as a result causes a shift of the peak position due to the imbalance of events [40]. The $m_{\gamma\gamma}^2 - m_H^2$ factor present causing a slight excess of events in the region $m_{\gamma\gamma} < m_H$, and a slight deficit of events in the region $m_{\gamma\gamma} > m_H$ which is the cause of the effective shift of the $gg \rightarrow H \rightarrow \gamma\gamma$ signal-only Breit-Wigner peak towards lower $m_{\gamma\gamma}$ values. Although the mass shift changes the shape of the peak, there is no effect on the total cross-section since the total integral over the $m_{\gamma\gamma}$ distribution remains unchanged. The theoretically predicted shift of the peak position due to interference in the SM is displayed in Figure 3.8a.

The imaginary-part of the interference is symmetric around the peak so does not directly distort the signal $m_{\gamma\gamma}$ lineshape as the real-part does, though instead affects the total cross-section. This imaginary component is strongly suppressed at LO, and the effects predominantly enter at NLO in QCD. The relative signs of the signal and background amplitudes are such that the imaginary-part of the interference is destructive in nature, and has been calculated to reduce the total cross-section by $\mathcal{O}(1\text{-}2\%)$ at NLO [43, 44].

The SM predicted $m_{\gamma\gamma}$ lineshapes corresponding to the real-part and imaginary-part of the interference are illustrated in Figure 3.8b, where the effect on the Breit-Wigner lineshape due to the resonant $gg \rightarrow H \rightarrow \gamma\gamma$ signal is also shown. The shape effect on the peak position due to the real component, along with the yield impact due to the imaginary component of the interference,

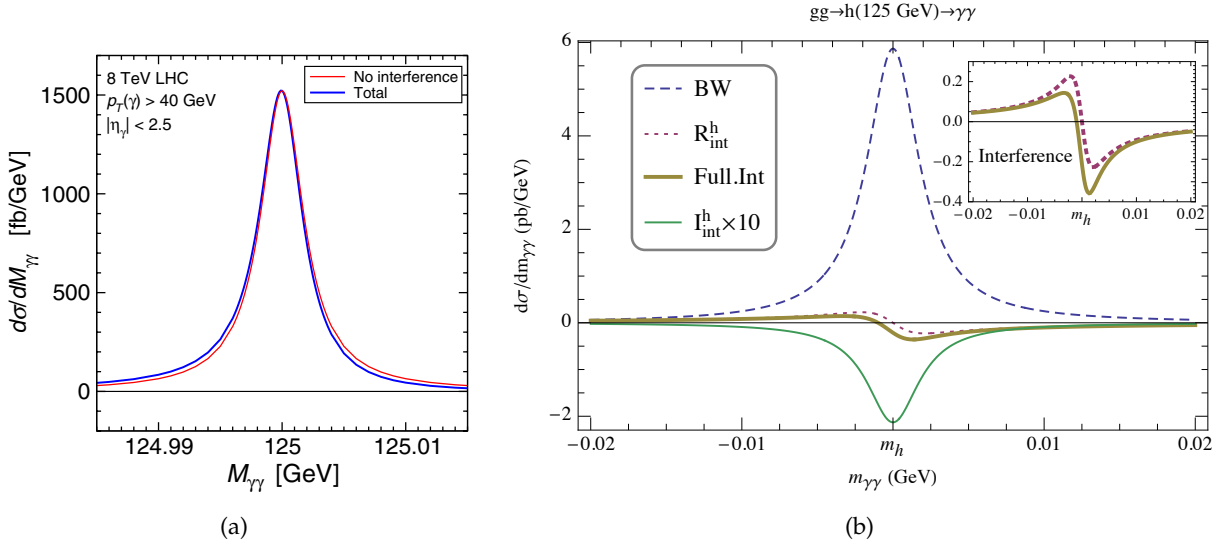


Figure 3.8: Diphoton invariant mass lineshape induced by various contributions in the SM: Figure 3.8a displays a comparison between the resonant signal only (blue), and the combined signal-interference lineshape (red) [42]; Figure 3.8b displays separately the Breit-Wigner (BW) lineshape of the resonant signal (blue dashed), the real-part of the interference (red dashed), the imaginary-part of the interference (green) which has been scaled by a factor 10 for visualisation purposes, and these interference components combined (brown) [43].

is what will be measured during the experimental analysis presented in this chapter. The brown line denotes the total interference lineshape. In this particular figure, the diphoton invariant mass has been scaled to centre around the input Higgs boson mass value of $m_H = 125$ GeV, such that the displayed $m_{\gamma\gamma}$ values are relative to this central value. Other sub-dominant interference contributions are also taken into account in the analysis; these will be discussed in section 3.3.2.

Experimental effects: The experimental detector resolution causes a *smearing* of the reconstructed photon energies, a process by which the energy distributions are broadened. This detector resolution affects the interference lineshape by smearing out the observed peak and dip structure of the lineshape. Consequently, this results in a dependence of the apparent mass shift observable in the $m_{\gamma\gamma}$ distribution, on the detector resolution. In theoretical predictions [40, 42], the detector resolution is accounted for by convoluting the $m_{\gamma\gamma}$ distribution with a Gaussian of width equal to the expected detector resolution. The resulting effect on the interference lineshape is depicted in Figure 3.9a where the change in shape of the real-part of the interference is shown, for different detector resolution hypotheses ranging between $\sigma = 1.3 - 2.4$ GeV. At the LHC, the expected combined resonant signal and interference $m_{\gamma\gamma}$ invariant mass distribution obtained is shown blue in Figure 3.9b, overlaid with the signal-only distribution shown in red. Note the significant difference in the $m_{\gamma\gamma}$ range between Figure 3.8a and Figure 3.9b, due to the impact of the experimental resolution. It is important to note that this simplified Gaussian smearing procedure is a simplification of the detector effects on the photon energies. It fails to account for the dependence on $p_T^{\gamma\gamma}$, the photon conversion status, and the variation in resolution as a function of the specific

geometric region where the photon energies are deposited, in particular η , (this will also depend on the individual detector, and thus be different for ATLAS and CMS). The only way to obtain a more accurate result is to simulate the full detector response, as well as a proper treatment of the individual experimental systematics when performing the $m_{\gamma\gamma}$ measurement. This has been done as part of the Higgs boson width analysis using $\gamma\gamma$ interferometry, which is presented in Chapter 6 of this thesis; further details will be outlined there.

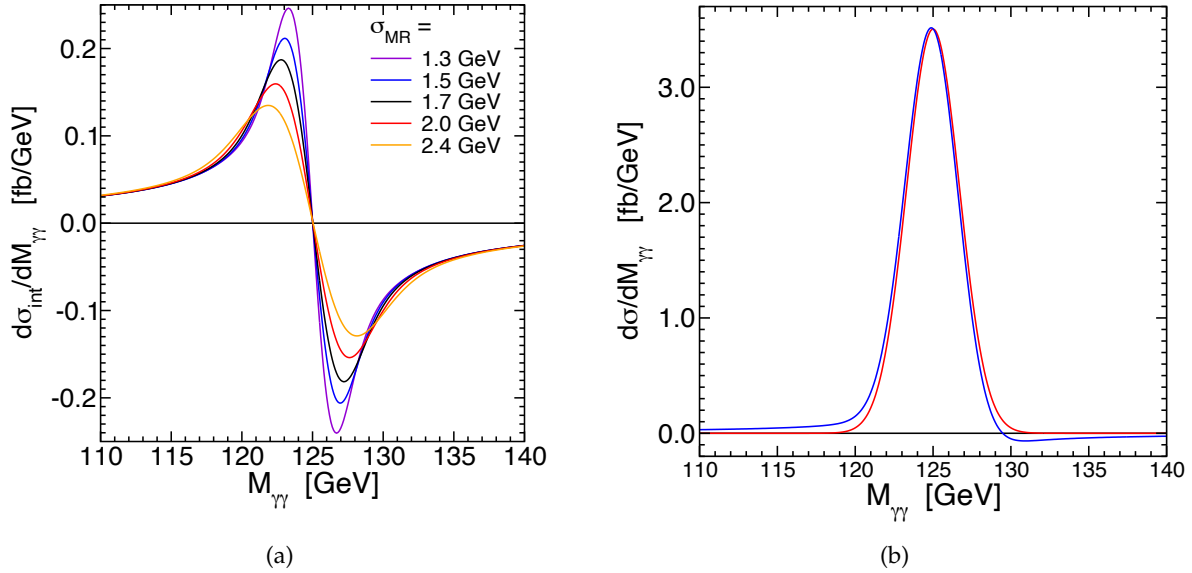


Figure 3.9: Diphoton invariant mass distributions illustrating the impact of including the experimental detector resolution. Figure 3.9a illustrates the effect of various detector resolution values on the real-part of the gg -interference contribution [40], while Figure 3.9b displays the effect of the interference (blue) on the signal-only lineshape (red), considering a detector resolution of $\sigma_{MR} = 1.7$ GeV [42].

3.3.2 Sub-dominant interference contributions

Higgs boson production may also occur through quark-gluon initiated processes, for which the tree level $qg \rightarrow q\gamma\gamma$ channel plays the role of the background. This is a sub-dominant contribution compared to the gg -initiated processes however, due to the smaller quark PDF in the case of the signal process. The $q\bar{q} \rightarrow Hg \rightarrow \gamma\gamma g$ process also contributes though is numerically minuscule [45, 42] and as such is not considered. Feynman diagrams corresponding to these processes at leading order are shown in Figure 3.10. The lineshapes due to the real component of each of these interference contributions, as a function of $m_{\gamma\gamma}$, are shown in Figure 3.11a. The total cross-section for the gg -interference is negative and roughly one order of magnitude larger than the positive qg -interference cross-section. As can be seen by the red dotted line, the $q\bar{q}$ contribution is effectively zero and so can be safely ignored.

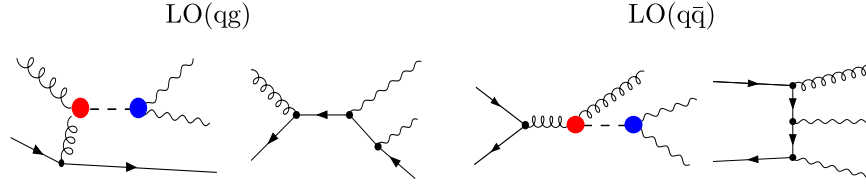


Figure 3.10: Feynman diagrams of the LO qg - and qq -interference contributions in the diphoton channel up to order α_s^3 [41]. In each pair of diagrams, the signal process is drawn on the left, whilst the background is on the right. The red dot indicates the effective vertex production vertex, whilst the blue dot denotes the effective vertex of the Higgs boson decay.

Although the dominant interference contribution arises from the $gg \rightarrow \gamma\gamma$ processes, the subdominant interference effects due to the qg -initiated processes should be also accounted for. The shape of the qg -interference is similar to that of gg contribution however there is a phase difference, so the overall effect on the Higgs boson signal peak is opposite with respect to the gg -interference, i.e. it shifts the signal $m_{\gamma\gamma}$ peak towards higher values. Both of these contributions are shown in Figure 3.11b, when including the effect due to the detector resolution (taking $\sigma = 1.7$ GeV). The total integral over the $m_{\gamma\gamma}$ lineshape is positive for the qg -interference, in contrast to the negative gg -interference cross-section. The LO and NLO calculations for the dominant gg -

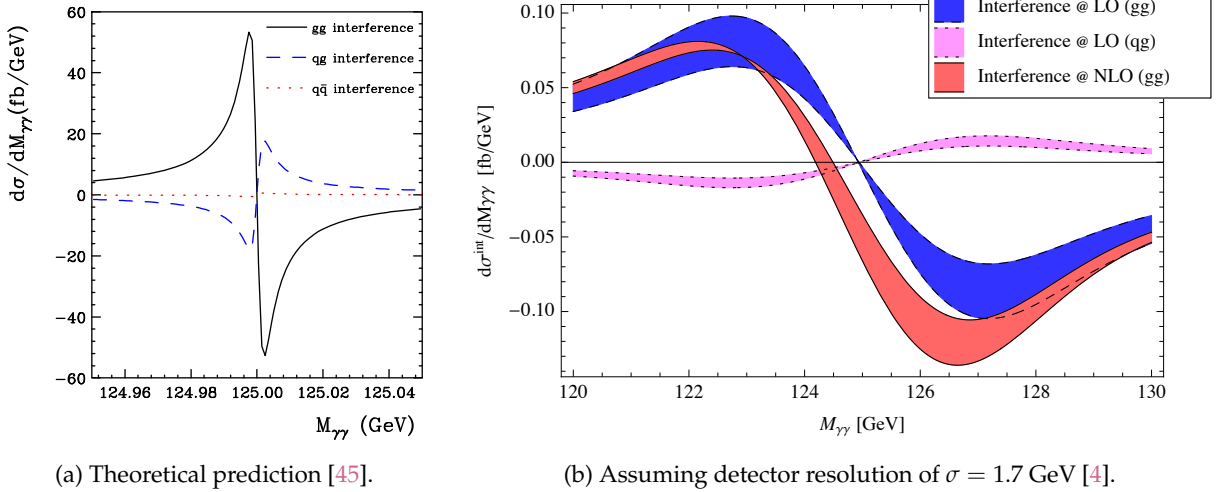


Figure 3.11: Diphoton invariant mass lineshapes for the interference contributions as 3.11a predicted by the SM theory at order α_s^2 , and 3.11b when including the experimental detector resolution. Figure 3.11b displays the gg -interference effect at LO (dominated by the real-part of the interference), and at NLO (where the imaginary-part also contributes).

interference contribution have been displayed separately, so the effect due to the imaginary-part, which is largely suppressed at LO, can be seen. Since the expected cross-section for this process is smaller than for the gg -interference, the net global effect due to the interference is still a mass shift towards lower $m_{\gamma\gamma}$ values, albeit slightly less than without accounting for the qg contribution.

3.3.3 Interference calculations beyond NLO

The most precise gg - and qg - interference cross-sections to-date have been calculated in [41] at NNLOsv, where the -sv suffix denotes that the soft-virtual approximation [46] was used. The $m_{\gamma\gamma}$ invariant mass lineshape arising from the combined effect of the interference contributions are shown in Figure 3.12a, where the effects due to the real-part (3.12b) and the imaginary-part (3.12c) are also displayed separately. In each case, the calculations done at LO, NLO, and NNLOsv are shown. At NNLOsv, the imaginary-part of the interference causes a 1.7% reduction with respect

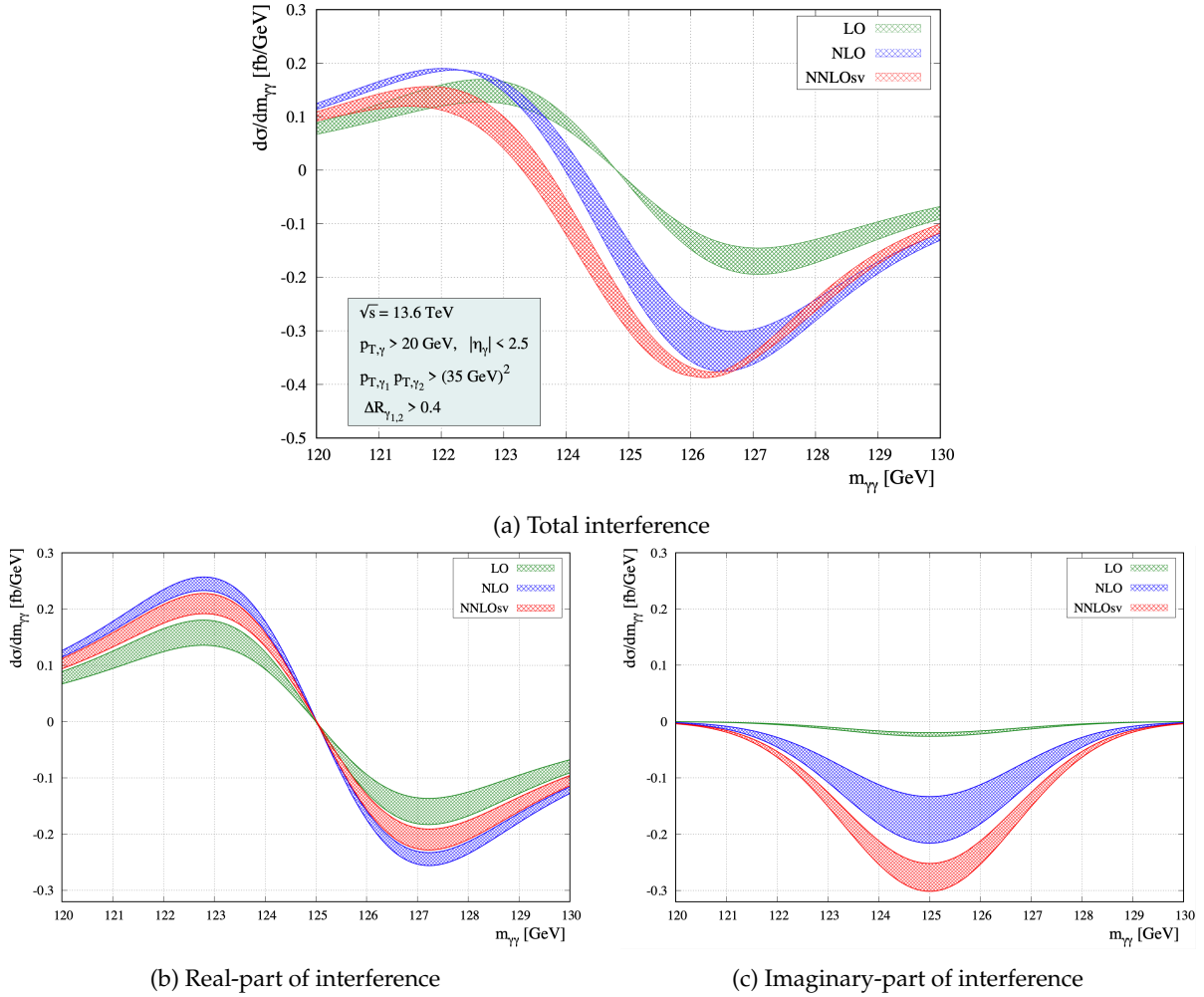


Figure 3.12: Signal-background interference process as a function of the diphoton invariant mass, $m_{\gamma\gamma}$ computed at LO (green), NLO (blue), and NNLOsv (red) after including ‘detector effects’ through smearing with a Gaussian of resolution $\sigma = 1.7$ GeV [41]. Figure 3.12a shows the combined interference lineshape, whilst Figures 3.12b and 3.12c show separately the real-part and imaginary-parts respectively. The uncertainty band corresponds to the envelope defined by the scale variations.

to the signal-only cross-section. The real-part instead is calculated to cause a $-39.4^{+6.3}_{-6.7}$ MeV mass shift in $m_{\gamma\gamma}$. This value has been determined by fitting the diphoton invariant mass distributions with a Gaussian and taking the difference between the obtained central value, and the reference input Higgs boson mass value of $m_H = 125$ GeV. These calculations have been undertaken

assuming a centre-of-mass energy of 13.6 TeV.

3.3.4 Calculating the mass shift, $\Delta m_{\gamma\gamma}$, and extracting Γ_H

There are various techniques proposed to measure the Higgs boson width by exploiting interference effects using the $m_{\gamma\gamma}$ distribution. The first is to directly calculate the mass shift observable, $\Delta m_{\gamma\gamma}$, which will be outlined in this section, followed by section 3.3.5 which will describe how a shape fit over the entire $m_{\gamma\gamma}$ distribution can be used to determine Γ_H .

When integrating the cross-section over $m_{\gamma\gamma}$, the signal term (from equation 3.14) is found to be proportional to $g_{ggH}^2 g_{H\gamma\gamma}^2 / \Gamma_H$, while the interference term instead is proportional to $g_{ggH} g_{H\gamma\gamma}$ [4], i.e. the signal plus interference cross-section is proportional to

$$\sigma \sim \frac{g_{ggH}^2 g_{H\gamma\gamma}^2}{m_H \Gamma_H} S + g_{ggH} g_{H\gamma\gamma} I, \quad (3.15)$$

where $I = I_{\text{Re}} + I_{\text{Im}}$. Noting here the different dependence of the integrated interference on the Higgs boson production and decay couplings, with respect to the signal. The current experimental measurements constrain the cross-section of the $H \rightarrow \gamma\gamma$ process to be within 10% of the SM prediction [47, 48, 49]. With this level of precision, the effect of I_{Im} on the cross-section can be considered negligible. Taking the ratio then between the observed impact of the I_{Re} component, with respect to the SM prediction, we obtain:

$$\frac{I_{\text{Re}}}{I_{\text{Re}}^{\text{SM}}} \propto \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}. \quad (3.16)$$

As described in the previous section, the effect of the interference lineshape due to I_{Re} including both gg - and qg -interference contributions, is a net mass shift towards lower values of $m_{\gamma\gamma}$, so $\Delta m_{\gamma\gamma} < 0$. As per equation 3.16, a measurement of the mass shift in the $m_{\gamma\gamma}$ distribution, which is due to the I_{Re} contribution, can thus be used to constrain the Higgs boson width, Γ_H . The size of this mass shift as a function of the Higgs boson width is calculated in [41] at NLO and NNLOsv; this is displayed in Figure 3.13.

From a theoretical perspective, a simplistic way to determine the mass shift is to define a mass window $|m_{\gamma\gamma} - m_{\text{peak}}| < \delta$ where m_{peak} is the mass value corresponding to the peak of the invariant mass distribution, and the mass range defined by δ should be sufficiently large that it covers majority of the $m_{\gamma\gamma}$ distribution where there's an excess of events present over the background events. The normalisation factor within this mass window is then defined as

$$N_\delta = \int_{m_{\text{peak}} - \delta}^{m_{\text{peak}} + \delta} dm_{\gamma\gamma} \frac{d\sigma}{dm_{\gamma\gamma}} \quad (3.17)$$

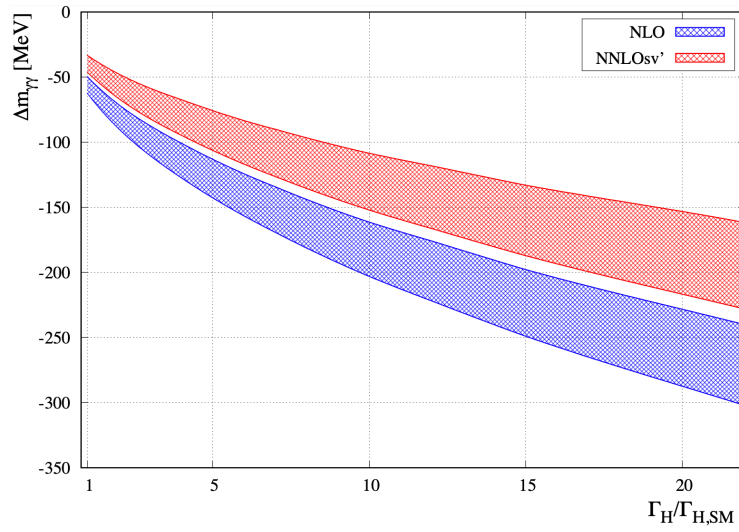


Figure 3.13: Mass shift, $\Delta m_{\gamma\gamma}$, as a function of the SM-normalised Higgs boson width [41]. The band corresponds to the scale variation uncertainties.

which allows for the mean value of the diphoton invariant mass distribution, $\langle m_{\gamma\gamma} \rangle_\delta$, to be calculated as

$$\langle m_{\gamma\gamma} \rangle_\delta = \frac{1}{N_\delta} \int_{m_{\text{peak}} - \delta}^{m_{\text{peak}} + \delta} dm_{\gamma\gamma} m_{\gamma\gamma} \frac{d\sigma}{dm_{\gamma\gamma}}. \quad (3.18)$$

The mass shift is then defined by taking the difference between two values of $\langle m_{\gamma\gamma} \rangle_\delta$: one computed where very little or no interference effects are present, known as the *reference mass*, and the second term computed when the interference contribution is included (denoted *total* since here all processes contributing to $gg \rightarrow (H \rightarrow) \gamma\gamma$ are present), i.e.

$$\Delta m_{\gamma\gamma} \equiv \langle m_{\gamma\gamma} \rangle_{\delta, \text{total}} - \langle m_{\gamma\gamma} \rangle_{\delta, \text{no interference}} \quad (3.19)$$

This procedure was used in [4] to theoretically determine the mass shift to be around 70 MeV at NLO in the SM, when a detector resolution of 1.7 GeV was considered. Since the tails of the interference invariant mass distribution extend much wider than the resonant signal, the value chosen for δ to define the mass window, has an effect on the resulting mass shift value obtained [40]. Actually $\Delta m_{\gamma\gamma}$ increases roughly linearly as a function of δ only when δ is greater than roughly two times the mass resolution, σ_{MR} . The dependence of the apparent mass shift on the detector resolution is shown in Figure 3.14, for resolution values within the range $\sigma_{\text{MR}} = 1.3 - 2.4$ GeV. Choosing a $\delta \gtrsim 1$ GeV is more aligned with the experimental method whereby the signal region is typically defined between $120 < m_{\gamma\gamma} < 130$ GeV (so $\delta = 5$ GeV). At this value of δ the mass shift is smaller for increasing values of σ_{MR} , which consequently dilutes the sensitivity to Γ_H .

All theoretical papers published thus far which calculate a prediction for the mass shift, and the

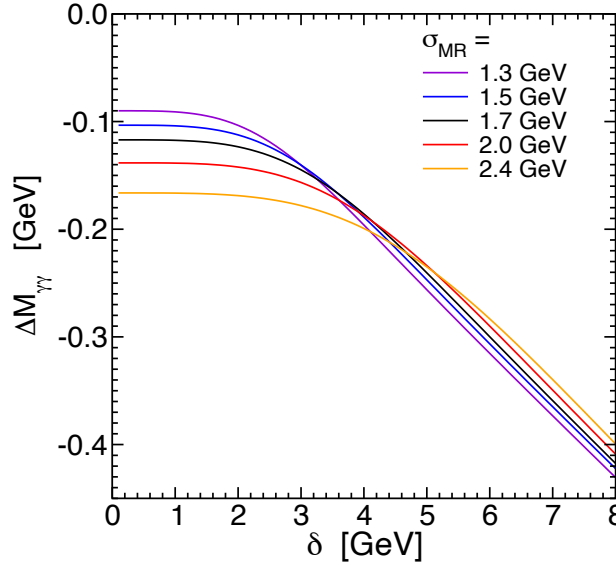


Figure 3.14: Mass shift, $\Delta m_{\gamma\gamma}$, computed at leading order as a function of δ used to define the considered mass window [40], as per equation 3.3.4. The dependence is shown for various values of the mass resolution, σ_{MR} .

dependence on Γ_H , all stress the importance of correctly taking into account the effects due to the finite detector resolution, and that this is only something that can be studied by the experimental collaborations. The scope of the analysis presented in Chapter 6 of this thesis includes accounting for such effects, by using the full simulation of the ATLAS detector response.

Experimentally, there are several potential methods to calculate the mass shift depending on how the two $\langle m_{\gamma\gamma} \rangle_\delta$ terms are defined, as per equation 3.3.4. The three main methods each use different decay modes, or physically different regions of phasespace defined by kinematic selections, to strategically choose the two regions used to define the mass shift; these will be discussed below.

Two decay channels ($\gamma\gamma$, ZZ^*): One possibility is to define the Higgs boson mass measurement in the $H \rightarrow ZZ^*$ decay channel as the reference mass (i.e. the second term in equation 3.3.4). Since the effects due to the presence of interference are much smaller in the ZZ^* channel, the mass shift can be obtained by taking the difference between the mass measured in the $\gamma\gamma$ channel, and the ZZ^* channel. The experimentally measured mass value, in any given channel, X , can be denoted as:

$$m_H^{\text{measured}, X} = m_H^{\text{true}} + \delta m_H^{\text{interference}, X}, \quad (3.20)$$

where m_H^{true} denotes the particles inherent invariant mass, and the $\delta m_H^{\text{interference}, X}$ term instead is the mass shift with respect to the true value due to interference effects, in a given channel, X . The mass shift computed by taking the difference between the measured mass values in two different

channels is thus defined as:

$$\Delta m_H \equiv m_H^{\text{measured}, \gamma\gamma} - m_H^{\text{measured}, ZZ^*} \quad (3.21)$$

$$= (m_H + \delta m_H^{\gamma\gamma}) - (m_H + \delta m_H^{ZZ^*}) \quad (3.22)$$

$$= \delta m_H^{\gamma\gamma} - \delta m_H^{ZZ^*} \quad (3.23)$$

$$= -80 \pm 490 \text{ MeV}, \quad (3.24)$$

where here the combined Run 1 ATLAS and CMS mass measurements have been used. The mass shift due to interference effects in the reference region (ZZ^* channel here) is negligible, hence as equation 3.23 demonstrates, the measured mass shift is entirely due to the effects in the $\gamma\gamma$ channel in this case. The uncertainty in equation 3.24 has a large statistical component, which will substantially improve by the end of the High-Luminosity LHC data-taking period. Already after Run 2, the systematic uncertainties dominate and so reducing them will be the real challenge for a measurement of this nature. The expected mass shift for a SM Higgs boson was estimated by ATLAS using the Run 1 dataset, through MC simulations of the interference with an approximate (rather than the full) detector description, and the expected shift was $\Delta m_H = -35 \pm 9 \text{ MeV}$ [50]. Note this result was not a measurement on data, but rather a determination of the *expected* mass shift value only. It is interesting to note that this mass shift is smaller than the leading sources of experimental systematics in the diphoton decay channel, which combined are now (end of Run 2) $\mathcal{O}(90 \text{ MeV})$ [51].

Two production modes (ggF, VBF): A possible way to circumvent using $H \rightarrow ZZ^*$ events to define the reference mass value, was proposed in [52], where it is shown that in the $pp \rightarrow H(\rightarrow \gamma\gamma) + 2 \text{ jet}$ channel, the ggF and VBF production modes generate mass shifts of opposite signs which largely cancel, depending on the specific set of kinematic selections applied. Events containing two final state jets can be identified through making selections on, for example, the invariant mass of the two leading jets in the event, m_{jj} , which are typically highly-energetic, or on the difference in pseudorapidity between the two jets, $|\Delta\eta_{jj}|$. It was found in [52] that the mass shift tends to zero as the minimum transverse momentum required for the Higgs boson increases. This is shown in Figure 3.15, where the dependence for ggF events (red), VBF events (blue) and these combined (black) are displayed. In this way, a mass measurement using $pp \rightarrow H(\rightarrow \gamma\gamma) + 2 \text{ jet}$ events could define the ‘no interference effects’ reference mass, instead of the $m_H^{ZZ^*}$ value used by the method in the previous section. The overall mass shift, Δm_H , is then defined by the difference between the measured value in the $pp \rightarrow (H \rightarrow) \gamma\gamma$ channel, and that measured in the $pp \rightarrow H(\rightarrow \gamma\gamma) + 2 \text{ jet}$ channel:

$$\Delta m_H^{\gamma\gamma} \equiv \delta m_H^{\gamma\gamma, \text{incl}} - \delta m_H^{\gamma\gamma, 2 \text{ jet}}. \quad (3.25)$$

The benefit of this method is that you can use only $\gamma\gamma$ events without having to compare against

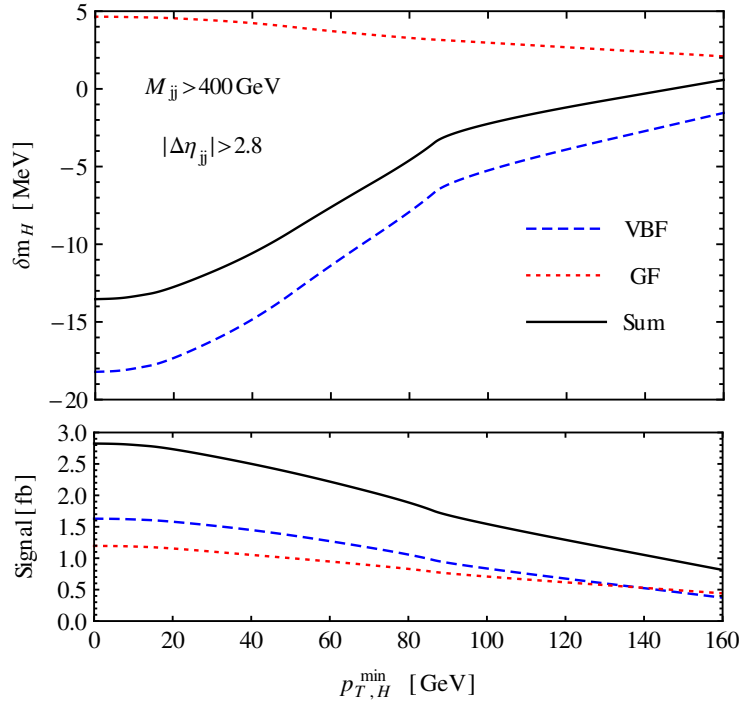


Figure 3.15: Dependence of the mass shift due to interference effects on several Higgs boson production modes, as a function of the lower p_T cut of the Higgs boson [52]. The mass shift corresponding to the gluon gluon fusion (ggF) production mode of the Higgs boson are shown in red, while the vector boson fusion (VBF) mode instead is shown in blue. The two leading jets satisfy $m_{jj} > 400$ GeV and $|\Delta\eta_{jj}| > 2.8$.

an external mass reference (e.g. $m_H^{ZZ^*}$) which leads to a (partial) cancellation of the experimental systematic uncertainties, in particular of those associated to the absolute photon energy scale. This is particularly important for determining the Higgs boson width since, as mentioned above, the systematic uncertainties are larger than the expected size of the mass shift.

Two kinematic regions (low $p_T^{\gamma\gamma}$, high $p_T^{\gamma\gamma}$): A third method initially studied and proposed in [4, 42], exploits an observed dependence of the mass shift on the diphoton transverse momentum, as shown in Figure 3.16. Using the ggF production mode only, different phasespace regions can be constructed by applying selections on $p_T^{\gamma\gamma}$ to define a region with large interference effects (low $p_T^{\gamma\gamma}$), and another with almost no interference effects (high $p_T^{\gamma\gamma}$ values). This dependence arises since the interference contribution is proportional to the combined amplitude of the signal and background process, and the peak in the $p_T^{\gamma\gamma}$ distribution for signal events is at low values. The overall mass shift is subsequently defined by:

$$\Delta m_H^{\gamma\gamma} \equiv \delta m_H^{\gamma\gamma, \text{low-}p_T^{\gamma\gamma}} - \delta m_H^{\gamma\gamma, \text{high-}p_T^{\gamma\gamma}}. \quad (3.26)$$

Similarly to the previous method, this procedure also exclusively uses $\gamma\gamma$ events.

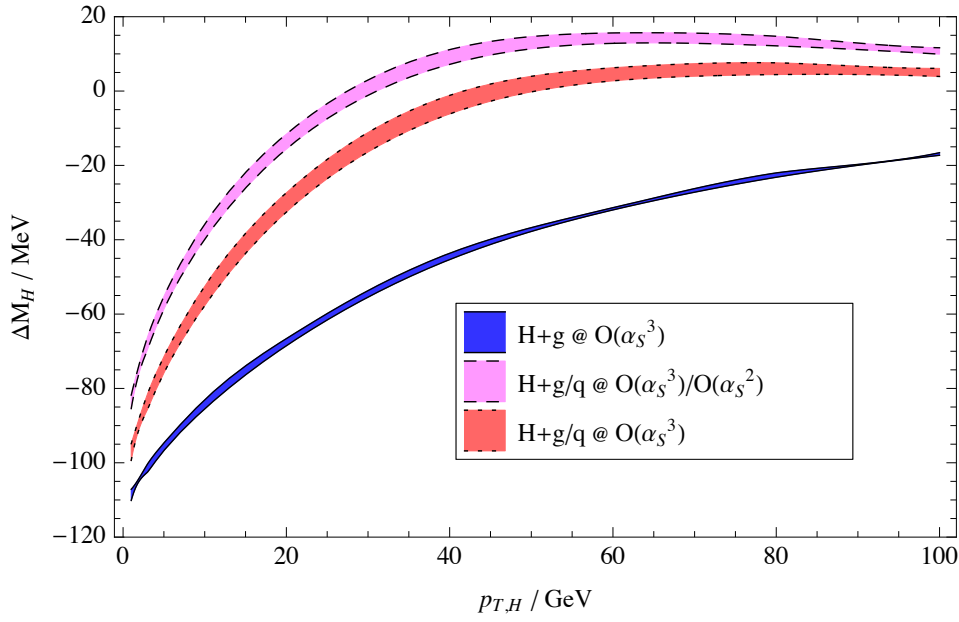


Figure 3.16: Higgs boson mass shift, $\Delta m_{\gamma\gamma}$ (labelled here as ΔM_H), as a function of the lower cut on the transverse momentum of the Higgs boson [4]. The blue line shows the dependence of the gg -interference only, on the transverse momentum at order α_s^3 , pink corresponds to the dependence of the gg - and qg -interference computed at order α_s^3 and α_s^2 respectively, while orange includes gg - and qg -interference contributions at order α_s^3 (note only some qg -interference $\mathcal{O}(\alpha_s^3)$ corrections are included, it is not a complete order α_s^3 calculation) where the expected mass shift plateaus around 0 when a lower cut on $p_T^H \geq 40$ GeV is applied. The uncertainty band is defined by the scale variations.

If we want to be sensitive to shape effects due to interference contributions over the whole $m_{\gamma\gamma}$ lineshape, the sensitive observable must be able to capture more than simply the shift in maximum values of the measured distribution. This is the essence of the method proposed in section 3.3.5.

3.3.5 Shape fit over $m_{\gamma\gamma}$ distribution

Instead of computing only the mass shift of the peak, an alternative method, and the method used for the main analysis presented in this thesis, aims to parametrise and perform a shape fit to the full $m_{\gamma\gamma}$ lineshape (blue line in Figure 3.9b), to capture the interference effects across the entire $m_{\gamma\gamma}$ spectrum. The intention is to define a simultaneous shape fit of the full $m_{\gamma\gamma}$ distribution across multiple event categories, defined by a set of selection criteria, which are able to exploit the fact that the interference effects are enhanced in different kinematic regions (as introduced in the previous section). This method is expected to be more sensitive to Γ_H since more information about the entire $m_{\gamma\gamma}$ lineshape is able to be included differentially, compared to simply calculating the shift in the maximum value of the distribution. Further details pertaining to the analysis strategy will be presented in Chapter 6.

The model-independent nature of this proposed measurement strategy makes it an ideal choice

for determining the Higgs boson total decay width, given the inherent sensitivity to BSM physics of this parameter. No assumptions are required on the coupling values, as was the case in the off-shell method. The exploitation of interference effects promises to be an invaluable probe for new physics arising in the Higgs boson width value.

4 | The Large Hadron Collider and the ATLAS experiment

Understanding the nature of fundamental particle interactions is inherently an experimental exploit. The ability to probe very small distances, requires an experimental machine capable of reaching sufficiently high energies. The highest energy particle accelerator globally is the Large Hadron Collider; it is the only facility capable of producing enough Higgs bosons to conduct experimental measurements thanks to the collision centre-of-mass energy, instantaneous luminosity, as well as the choice of colliding proton beams. The LHC was proposed to outperform its predecessors being the Tevatron $p\bar{p}$ collider at Fermilab, and the Large Electron Positron (LEP) e^+e^- collider at CERN in terms of both the centre-of-mass energy and the instantaneous luminosity. The design collision energy of the LHC is 14 TeV; the design luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The design luminosity was reached in June 2016, while a centre-of-mass energy of 13.6 TeV has been achieved in 2023. The research presented in this thesis uses the ATLAS detector to capture the particles produced as a result of the LHC proton-proton collisions. The ATLAS detector is one of four LHC experiments. This chapter begins with an overview of the LHC facility, details the nature of proton-proton collisions, and provides a description of the ATLAS detector including the main detector sub-components, and how each is used to capture information from different particle types.

4.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular particle collider located at the *Conseil Européen pour la Recherche Nucléaire* (CERN) laboratory near Geneva, on the border between Switzerland and France. The LHC is a proton-proton (pp) collider, and has been operating at the energy frontier for the past decade. The collider consists of a 27 km ring, located approximately 100 metres underground, where two beams of protons are accelerated in opposite directions and are made to collide at specific interaction points. During the LHC collision periods, the proton collisions occurred at a centre-of-mass energy, $\sqrt{s}$, between 7 and 13.6 TeV. Figure 4.1 gives a cross-sectional view of the underground LHC ring, and its geographical position.

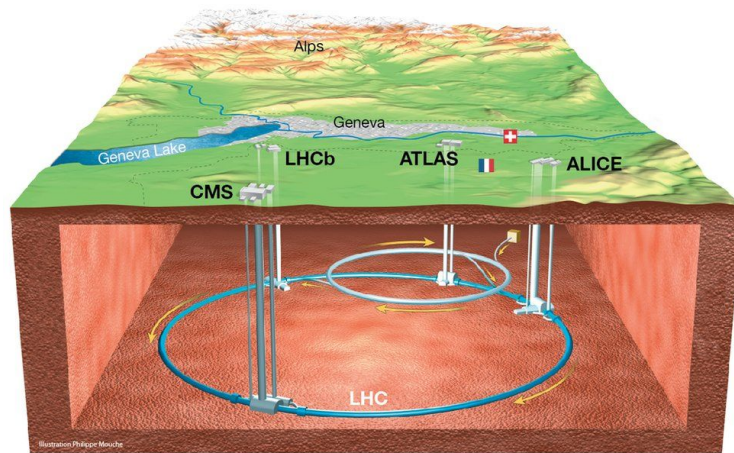


Figure 4.1: Cross-sectional view of the LHC ring, which sits ~ 100 m underground. The location of the four main LHC experiments are indicated. Image credit: Philippe Mouche, CERN.

There are four locations around the LHC ring where collisions occur, known as interaction points (IP). At each of these interaction points sits one detector: ATLAS (A Toroidal LHC ApparatuS), ALICE (A Large Ion Collider Experiment), CMS (Compact Muon Solenoid) and LHCb (Large Hadron Collider beauty) are the four LHC experiments. The locations of these detectors are labelled in Figure 4.1. ATLAS and CMS are two multi-purpose detectors where the aim is to collect as many interesting events as possible for a wide range of analyses. The benefit of having two general purpose detectors is that any major discovery made by one of the experiments is subject to cross-confirmation by the other. The collisions of proton bunches at the ATLAS interaction point occurs once every 25 nanoseconds, corresponding to roughly 7.5 metres separation.

4.1.1 Accelerator complex

The main components of the CERN accelerator chain are shown in Figure 4.2. The LHC is built using the infrastructure of the accelerators of the years prior, such that each machine injects the beam to the next in succession (each with a larger diameter than the previous), allowing the beam to be tuned and brought to higher energies as a result. Protons are injected into the two beams, each circulating in opposite directions. The LHC chain is comprised of five individual accelerators:

- The linear accelerator (LINAC) accelerates protons up to 50 MeV;
- The synchrotron booster (BOOSTER) increases that energy to 1.4 GeV;
- The proton synchrotron (PS) further accelerates the protons to 25 GeV;
- The super proton synchrotron (SPS) accelerates them further up to 450 GeV;

- Protons are then injected into the main LHC ring, which accelerates the protons up to the collision energy of 13 TeV. In total it takes roughly 20 minutes from beam injection until the nominal energy is reached.

The LHC ring is divided into alternating straight and curved segments; eight of each in total are present around the ring which act to accelerate and bend the two beams. To be able to bend the beams at energies half the collision energy, superconducting dipole magnets (1232 in total) made from Niobium - Titanium are required, which each produce an 8.3 T magnetic field. Superconductive electromagnets possess zero electrical resistance, which allows for a much larger electrical current than would otherwise be possible. This superconductivity is achieved by bathing the magnets in a 1.9 degree K helium superfluid, at 1 atm pressure. Interestingly, this temperature is colder than outer space, which has been measured to be $2.7\text{ K} \equiv -270^\circ\text{C}$ [53]. The four interaction points are all situated within one of the straight segments.

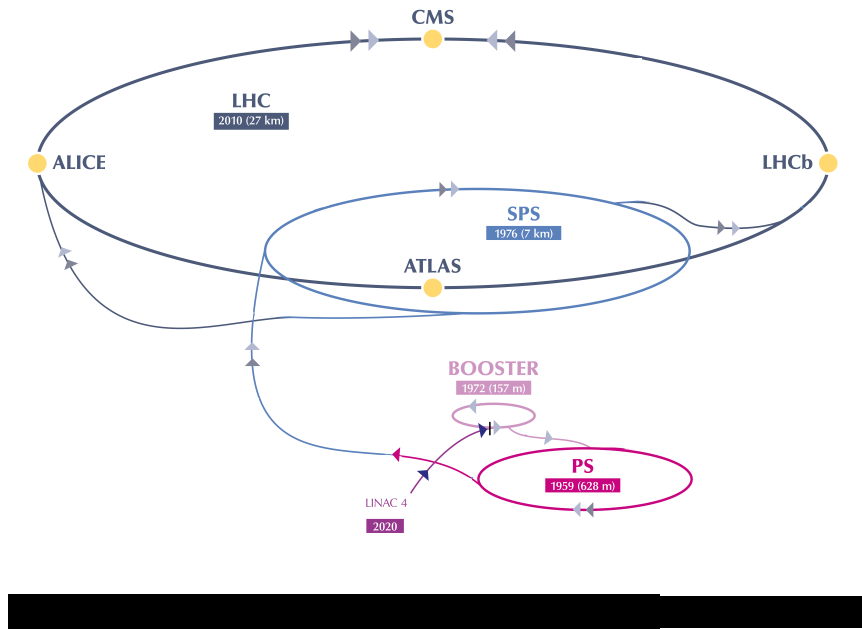


Figure 4.2: Diagram of the CERN accelerator complex, where the five main accelerator stages are shown, with the LHC being the final ring increasing the proton beams to reach the nominal collision energy. The interaction points of the LHC are indicated with a yellow circle at four locations around the ring. Diagram adapted from [54].

In addition to the four main LHC experiments previously mentioned, numerous smaller experiments also exist around the beam pipe to study for example properties of the beam itself, or search for exotic particles which may be produced at extremely forward angles that would be missed by the main experiments. Additional small detectors in close proximity to the ATLAS detector also exist. For example the LUCID-2 (Luminosity Cherenkov Integrating Detector) detector [55], consisting of multiple PMTs, sits 17 m further along the beam pipe from the ATLAS interaction point,

and is used to monitor and measure the instantaneous luminosity delivered to ATLAS.

4.1.2 Cross-sections and luminosity

Protons at the LHC are grouped into *bunches* each containing approximately 10^{11} protons. When the two proton beams circulating in opposite directions are made to cross, these bunches subsequently overlap at a rate of once every 25 nanoseconds, as illustrated in Figure 4.3. Out of these hundreds of billions of protons, only a tiny fraction (about 50 for each bunch crossing) of the protons actually collide, while the majority pass through the incoming bunch unaffected. An *event* is defined by the collisions that occur during one bunch crossing.

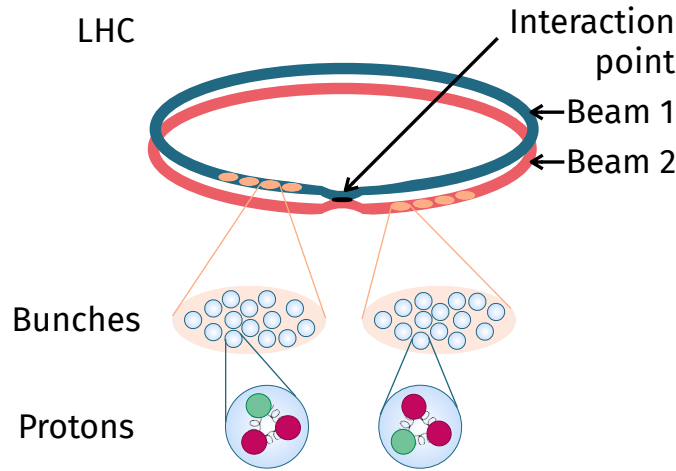


Figure 4.3: Diagram of the nature of pp collisions at the LHC. Protons are accelerated around the LHC ring in bunches. These bunches, containing 10^{11} protons, are made to collide at designated interaction points. Collisions occur between partons, i.e. between quarks and gluons that make up the individual protons.

The expected number of events, or the yield N_X , for a certain process $pp \rightarrow X$ with cross-section $\sigma_{pp \rightarrow X}$, is defined in equation 4.1.

$$N_{pp \rightarrow X} = \sigma_{pp \rightarrow X} \times \int \mathcal{L} \cdot dt, \quad (4.1)$$

where the total integrated luminosity, $\int \mathcal{L} \cdot dt$, is a measure for the number of colliding protons in a given period on time. The total integrated luminosity is usually expressed in units of inverse barns, and the cross-section is defined in units of barn, where 1 barn is equivalent to 10^{-24} cm^2 . The instantaneous luminosity, $\mathcal{L}_{\text{inst.}}$, is a property of the individual collider and in the case of a circular collider is defined in terms of the number of colliding bunches, n_b , the number of inelastic interactions per bunch crossing, μ (known as *pileup*), the bunch revolution frequency ($f_r = 11,246 \text{ Hz}$ for protons at the LHC), and the cross-section of inelastic pp collisions, $\sigma_{\text{inel.}} = 80 \text{ mb}$ for 13

TeV collisions, i.e.

$$\mathcal{L}_{\text{inst.}} = n_b \frac{\langle \mu \rangle f_r}{\sigma_{\text{inel.}}} \quad (4.2)$$

Specific parameter values determined for the 2015 – 2018 LHC pp collision period at $\sqrt{s}$ are listed in Table 4.1. After selecting a subset of the total events which pass the data quality criteria, the total integrated luminosity suitable for ATLAS physics analyses is $140.1 \pm 1.2 \text{ fb}^{-1}$. What deems collected data as being *suitable* for analysis firstly refers to stable beams being attained by the LHC, the ATLAS trigger systems and all sub-detectors being operational and actively recording data, as well as the data passing certain data quality checks [56].

Parameters	2015	2016	2017	2018
n_b	2232	2208	2544	2544
$\mathcal{L}_{\text{peak}} [10^{33} \text{ cm}^{-2}\text{s}^{-1}]$	5	13	16	19
Peak $\langle \mu \rangle$	16	41	60	55
$\int \mathcal{L}_{\text{inst.}} \cdot dt$ (delivered) [fb^{-1}]	4.0	39.0	50.6	63.8

Table 4.1: LHC parameters used for the total integrated luminosity during the 2015 – 2018 data-taking period, where pp collisions took place at $\sqrt{s} = 13 \text{ TeV}$. All values quoted are taken from [57].

Consider the $gg \rightarrow H \rightarrow \gamma\gamma$ process, the cross-section of this channel is determined by multiplying the ggF production cross-section of the Higgs boson, by the branching fraction of the $H \rightarrow \gamma\gamma$ decay. The cross-section of this specific process is computed to be $\sigma_{gg \rightarrow H \rightarrow \gamma\gamma} = 101.6 \text{ fb}$. This allows us to calculate the expected number of such events in 140.1 fb^{-1} of data, using equation 4.1, as $N_{gg \rightarrow H \rightarrow \gamma\gamma} = 14,234$ events.

4.1.3 Data-taking periods

The pp collision schedule of the LHC, defines the time periods of data-taking for each of the LHC experiments. The LHC data-taking periods are grouped into segments known as *Runs*. Run 1 occurred during 2011 – 2012 at $\sqrt{s} = 7 - 8 \text{ TeV}$ collecting a total of 24.9 fb^{-1} data useable for physics analysis. Following a shutdown period, Run 2 occurred between 2015 – 2018 at $\sqrt{s} = 13 \text{ TeV}$ collecting a total of 140.1 fb^{-1} of data. The main analysis presented Chapter 6 of this thesis uses the Run 2 dataset. Run 3 commenced in 2022 at $\sqrt{s} = 13.6 \text{ TeV}$ and is expected to last until 2025. Following each Run, a scheduled shutdown period takes place where any required detector maintenance and necessary upgrades can occur. The three LHC data-taking runs are together known as *Phase I* of the LHC. Following the completion of Run 3, the entire LHC facility will be shutdown in order to upgrade the machine to a higher luminosity version, known as the High Luminosity Large Hadron Collider (HL-LHC). HL-LHC pp collisions are scheduled to commence in 2029 at $\sqrt{s} = 14 \text{ TeV}$, and this will constitute the commencement of the *Phase II*

LHC data-taking program. Details pertaining to the HL-LHC upgrade are presented in Chapter 7.

The cumulative integrated luminosity collected by the ATLAS detector over the 2015 to 2018 data-taking period is shown in Figure 4.4a. ATLAS recorded roughly 94% of the total data delivered by the LHC, where 89% was deemed suitable to use for physics analyses. Figure 4.4b displays the mean number of interactions per bunch crossing distributions as weighted by the luminosity (pileup), for each of the four data-taking years, as well as the total. The mean pileup for Run 2 was $\mu = 33.7$.

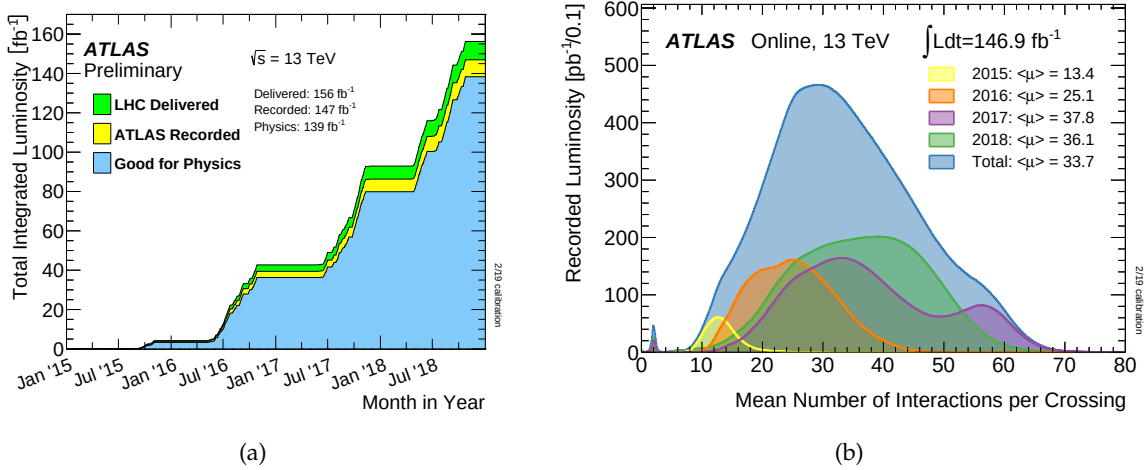


Figure 4.4: Total integrated luminosity as a function of time over the duration of the Run 2 data-taking period (4.4a) [58]. Distribution of the luminosity-weighted pileup (mean number of interactions per bunch crossing) values (4.4b) [58].

4.2 The nature of hadronic collisions

Interactions between protons at the LHC are described using the theory of QCD which was introduced in section 2.1.2. A theoretical overview of the nature of proton-proton collisions will now be discussed given the LHC is a proton-proton collider. A *parton* refers to either of the particle constituent types inside a hadron, be it a quark or gluon. Interactions between colliding protons at the LHC are between any of the partons. Interactions are classified in terms of the total momentum transfer as either *soft* or *hard* scattering events. Hard scattering processes corresponds to those where a large momentum transfer has occurred, and these are typically rarer events. The fraction of the total proton momentum carried by the individual partons is defined as the Björken variable, denoted x . The momentum distribution functions of partons are known as Parton Distribution Functions (PDFs) which depend on the energy scale μ^2 .

Non-perturbative QCD effects dominate physics inside hadrons (between the constituents), whilst interactions between partons belonging to different hadrons is described by perturbative QCD

calculations. The cross-section for two colliding protons ($pp \rightarrow X$) is defined by the convolution of their respective PDFs and the partonic cross-sections, thanks to the factorisation theorem [59], and can be expressed as:

$$\sigma_{pp \rightarrow X} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij \rightarrow X}(x_1, x_2), \quad (4.3)$$

where $f_i(x_1, \mu^2)$, $f_j(x_2, \mu^2)$ define the two PDFs at a specific energy scale; the indices i and j run over all partons involved in the collision. The partonic cross-section, $\hat{\sigma}_{ij}$ corresponds to the cross-section for the hard scattering component of the event, for the process $i j \rightarrow X$. The centre-of-mass energy for the partonic collision is then defined as $\sqrt{\hat{s}} = x_i x_j \sqrt{s}$, where $\sqrt{s}$ is the centre-of-mass energy of the pp collision as usual. The scale, μ^2 , defines the boundary between what is classified as hard scattering, and soft scattering physics. One of the main drawbacks of hadronic collisions is that after the colliding partons are extracted, what remains in the event is known as the *underlying event* which largely consists of soft interactions (therefore meaning perturbative QCD does not apply). Interactions involving low momentum transfer are the dominant source of background processes at hadron colliders, though can often be removed with appropriate selection criteria. These types of events occur much more frequently than the usually desired hard scattering events, making the overall environment a dense and busy one.

Figure 4.5 displays the PDFs evaluated at two different energy scales, $\mu^2 = 10 \text{ GeV}^2$, and $\mu^2 = 10^4 \text{ GeV}^2$, where the function $xf(x, \mu^2)$ is shown for partons g , u , $\bar{u}$, d , $\bar{d}$, and $s = \bar{s}$ ¹ as a function of its momentum fraction x , for each considered energy scale. At low x the number density for the gluon dominates, while at ultra high x the valence u - and d -type quarks dominate. The functions presented in Figure 4.5 are from the NNPDF collaboration [61] and are of particular relevance for the analysis presented in this thesis, as they are the PDFs used to simulate the contributing processes (more details in section 6.2).

4.3 Event generation and simulation

Monte Carlo (MC) event generators are the most prevalent way to simulate proton-proton collision events, and are used to simulate all aspects of the event from the matrix element calculation to the parton hadronisation. This is achieved in stages: starting with the parton distributions, the hard scattering event, then moving to the hadronisations and decay processes. MC generators rely on numerical methods to simulate so-called *truth* events, which correspond to simulating the physical processes but not including the detector response.

An example of a typical proton-proton collision, defined as an event, is shown in Figure 4.6. Aside from the hard scattering component, the remaining proton remnants are also still present and

¹ $s = \bar{s}$ since the difference between the calculated PDFs is compatible with zero [60].

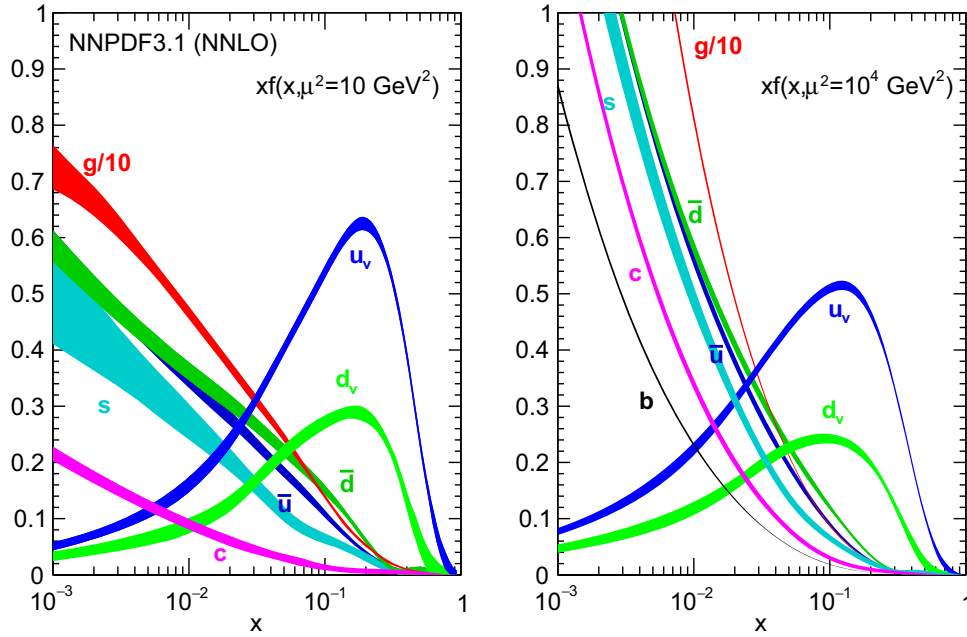


Figure 4.5: Parton distribution functions at next-to-next-to-leading order in QCD [61], for $\mu^2 = 10 \text{ GeV}^2$ (left), and $\mu^2 = 10^4 \text{ GeV}^2$ (right). The presence of the v subscript indicates those are valence quarks (as opposed to sea quarks).

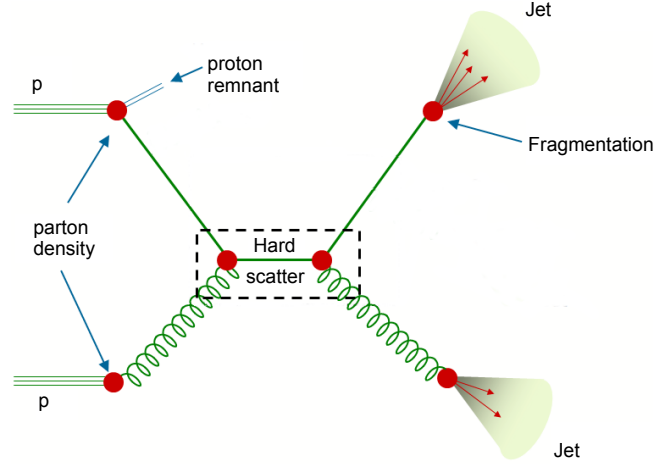


Figure 4.6: Diagram illustrating a typical proton collision, where the partons collide to define the hard scattering event, and subsequently hadronise into jets which are then reconstructed in the detector [62].

can partake in QCD interactions. Due to the nature of QCD as described in section 2.1.2, any free parton in the final state will hadronise and produce collimated jets as illustrated by the yellow cones on the right hand side of Figure 4.6. Radiative emissions that do not derive from the hard scattering component are known as either *initial state radiation* (ISR) or *final state radiation* (FSR), depending if they radiated off the initial state or final state particles respectively. The cascade of particles produced by the emission of further radiation (since gluons can couple to themselves),

is known as a *parton shower*. As already described in section 4.2, these cannot be described using perturbative QCD. Consequently they are modelled using various MC methods which simulate the emission according to some pre-defined order, for example decreasing p_T . These models make certain assumptions in the MC generation algorithm, and consequently the simulated events carry an associated modelling uncertainty.

The primary factor to take into account when selecting which MC generator to use, is whether it can simulate your specific process of interest, and at what order in the matrix element. Naturally, a generator that can simulate a process at higher order, will be more accurate than one at lower order. SHERPA (Simulation for High-Energy Reactions of PArticles) [63] is an example of one MC event generator which is able to entirely simulate both hadronic and leptonic collisions at high energies, and provide complete final states. This particular generator is important as it is the predominant choice for the MC simulation of processes required for the analysis presented in this thesis. The main reason for this choice is because the Sherpa authors were already privately working on including $H \rightarrow \gamma\gamma$ interference events in this generator, where as no other generators had the same capability. The matrix element calculation is performed in Sherpa using its own AMEGIC++ [64] and COMIX [65] matrix element generators. The default parton showering algorithm used is the CSSHOWER++ [66] algorithm which is built on the Catani-Seymour dipole factorisation [67, 68]; the DIRE [69] algorithm is an alternate parton showering possibility. Difference between these parton showering algorithms will be investigated and detailed during the analysis presented in Chapter 6.

Detector simulation (which produces simulated so-called *reconstructed* events) is achieved by firstly passing the *truth* MC generated events through a simulation of the ATLAS detector response, using a software toolkit known as GEANT4 [70]. This models the particle interactions with the detector material, so to simulate how the real events would behave as they traverse the detector layers. The second stage of this process is known as *digitisation*, whereby these simulated interactions are converted into simulated detector signals in the form of hits or energy deposits, so to replicate the information recorded by the detector. These hits or energy deposits are then directly equivalent to the information recorded by the detector components (as will be described in section 4.4). Finally, the event reconstruction procedure is the same for both MC simulated events and recorded data events. The diagram in Figure 4.7 broadly summarises all steps involved in the procedure, for both the MC simulated events, as well as data. The methods used to reconstruct and calibrate the events are presented in Chapter 5, once a description of the ATLAS detector has been presented.

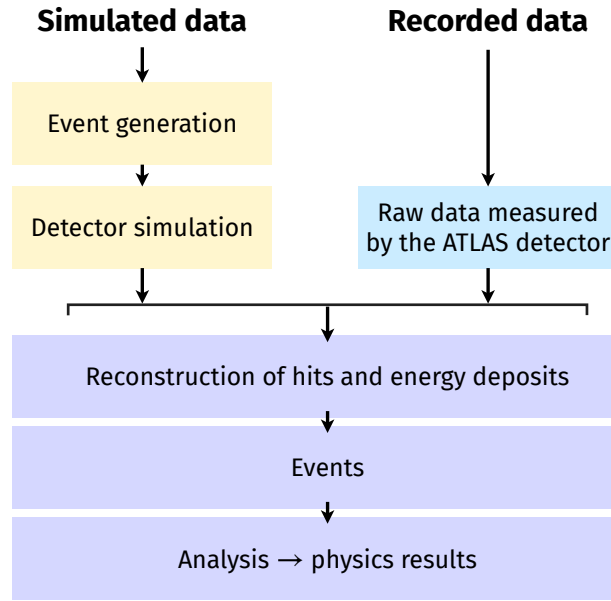


Figure 4.7: Procedure followed to obtain events, either through the collection of data recorded by the ATLAS detector, or by simulating data using a Monte Carlo generation method.

4.4 The ATLAS detector

The ATLAS detector [71] is a 7000 t, 44 m long and 25 m diameter multi-purpose detector. The initial physics goals for the ATLAS detector were to probe the origin of mass through searches for a Higgs boson like particle, measure fundamental SM parameters including particle properties, and to explore unprobed regions. The broad discovery potential of the machine is due to its sensitivity to a wide range of final state signatures through conducting e , γ , μ , jet and missing transverse energy measurements [72]. Following the Higgs boson observation in 2012, the ATLAS physics programme has entered a Higgs boson precision measurement era in the last decade, whilst in parallel still conducting extensive searches for exotic particles and beyond the SM physics.

A diagram of the ATLAS detector is shown in Figure 4.8, where the various detector components are labelled, each being responsible for detecting different types of particles and thus rely on specific technology and equipment to do so. The main four sub-detector systems, ordered by their proximity to the interaction point, are:

- the inner detector (ID) system is responsible for identifying and reconstructing charged particle trajectories, as well as the reconstruction of primary and secondary vertices;
- the electromagnetic (EM) calorimeter measures the direction and energy of photons and electrons;

- the hadronic calorimeter measures the direction and energies of neutral and charged hadrons;
- the muon spectrometers (MS) are responsible for the detection, identification and reconstruction of muons.

Two geometrical regions of the detector can be defined; the *barrel*, and the *end-cap*. The barrel is centred around the beam line and is cylindrical in shape. The end-caps correspond to two additional detectors located at either end of the central barrel. This barrel-end-cap design achieves $\sim 99\%$ coverage, almost 4π , of the full solid angle around the interaction point. ATLAS uses a unique combination of superconducting magnets; a solenoid, a barrel toroid and an end-cap toroid. The solenoid field is aligned along the beam axis where it delivers a 2 T magnetic field to the inner detector. The barrel and end-cap toroidal magnetic fields are 0.5 T and 1 T in strength respectively, and provide a magnetic field to the outer component of the detector. These magnetic fields cause charged particles to curve as they traverse the detector layers, allowing information about the particles momenta to be obtained.

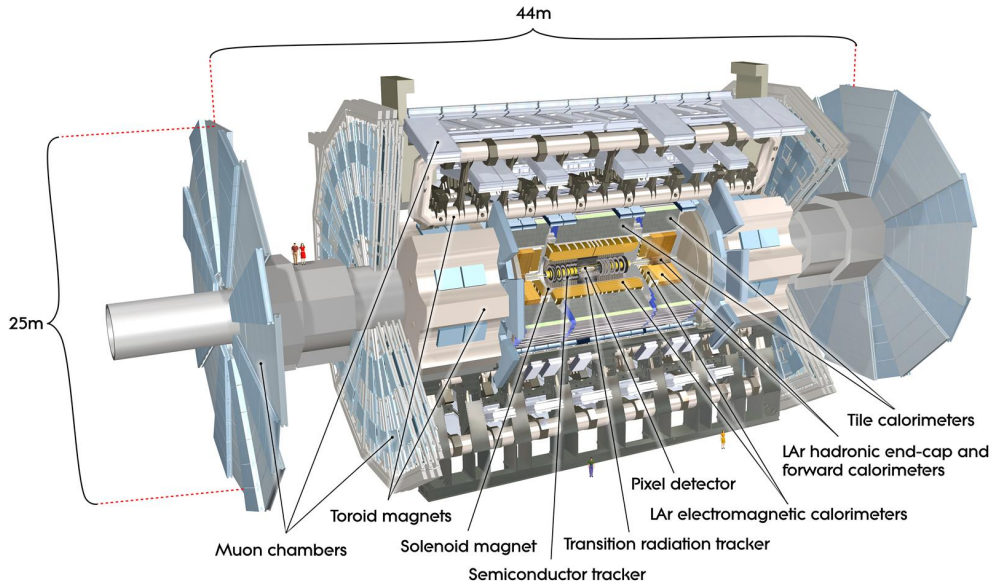


Figure 4.8: A diagram of the ATLAS detector [73]; each of the sub-components are labelled. For scale there are two people positioned on the left side of the diagram.

The principle detector technology used by each of the four aforementioned sub-detectors will be outlined in sections 4.4.2 to 4.4.4 respectively. Further details can be found in the references linked for each individual sub-detector. To perform the $H \rightarrow \gamma\gamma$ measurement presented in this thesis,

the electromagnetic calorimeter is the most important sub-detector given the two final state photons deposit their energy there. Additionally the tracking system must provide accurate spatial resolution to reconstruct the diphoton primary vertex from the hard scattering event, since track information as well as reconstructed photon candidates are used to identify the diphoton vertex via a neural network algorithm. Further details on the primary vertex identification procedure will be given in Chapter 5.

4.4.1 Coordinate system

The ATLAS detector uses a right-handed coordinate system to define kinematic variables. The beam direction is the z axis, the x axis points to the centre of the LHC ring, and the y axis is perpendicular to the z axis pointing away from the Earth's core. Polar coordinates are most commonly used to define the location of particles within the detector geometry. The polar angle θ is between the z axis and a particle's momentum vector. The azimuthal angle ϕ is defined in the x - y plane. These coordinates are shown in Figure 4.9 with respect to the LHC ring.

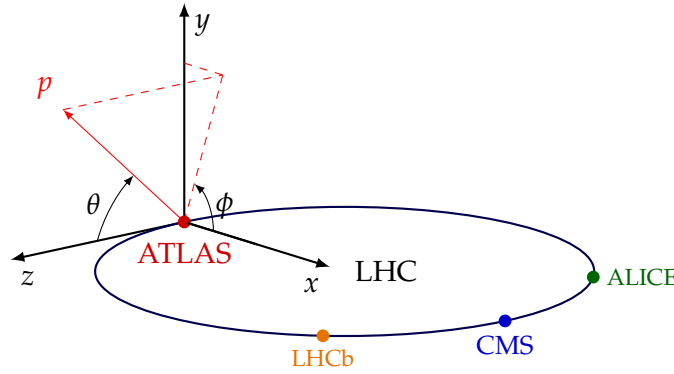


Figure 4.9: The coordinate system of the ATLAS detector. p indicates the momentum vector of a given particle.

A commonly used quantity at hadron colliders is the *pseudorapidity*, η , which is defined in terms of the polar angle as:

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right). \quad (4.4)$$

The angular distance between particle tracks is quantified in terms of ΔR in the η - ϕ plane, defined by:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (4.5)$$

When hadrons collide, the fraction of momentum carried by the individual partons involved in the collision is undetermined. For this reason, transverse components of kinematic variables are commonly used in ATLAS, and more generally in high-energy collider physics analyses since, to good approximation, the sum of momentum in the transverse plane is zero before the collision

occurs. The definition of transverse momentum p_T , and transverse energy E_T can be expressed as:

$$p_T = p \cdot \sin\theta, \quad E_T = E \cdot \sin\theta = \sqrt{m^2 + p_T^2}, \quad (4.6)$$

where p is the magnitude of a particle's three-momentum vector, and E is the total energy deposited in the detector layers. These quantities are necessary to identify missing transverse energy, which is characteristic of an event involving the presence of neutrinos in the final state since they're unable to be directly detected by ATLAS.

4.4.2 Tracking system

The ID is the tracking system of the ATLAS detector responsible for measuring energy deposits left by charged particles (*hits*) that can be used to reconstruct particle trajectories (*tracks*) within $|\eta| < 2.5$, and identify primary and secondary vertices originating from the hard scattering event. This innermost sub-detector directly surrounds the interaction point, and is itself comprised of three complementary components which each make use of distinct detection techniques: the silicon pixel detector, the silicon SemiConductor Tracker (SCT) and the straw drift tube Transition Radiation Tracker (TRT). These are all immersed within the solenoid magnets which provide a 2 T magnetic field. Figure 4.10 displays the various ID sub-systems, which are split into their barrel and end-cap components. The barrel region components are arranged in concentric cylinders at various radii out from the interaction point, starting from a radius $R = 33.25$ mm and extending to $R = 1082$ mm (combining all sub-systems of the ID). Any particle activity occurring between the interaction point at $R = 0$ mm and $R = 33.25$ mm occurs within the beam pipe where there is no detector material. The ID, in particular the silicon components, must be radiation tolerant given their proximity to the interaction point which is an extremely high radiation environment.

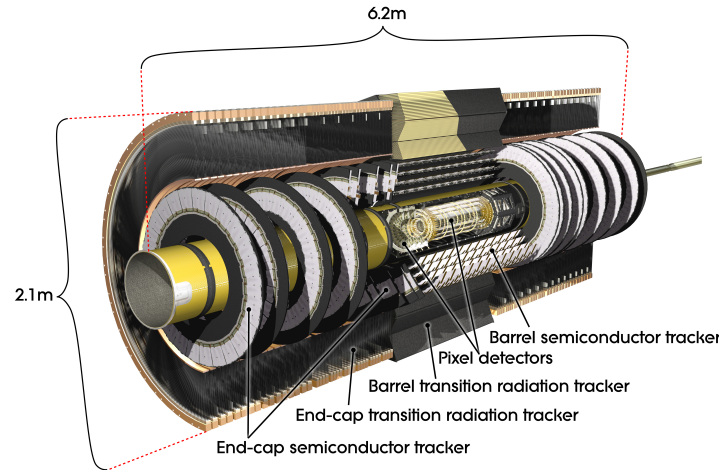


Figure 4.10: An overview of the inner detector components; the pixel detector surrounds the interaction point, followed by the SCT, and finally the TRT [71].

Pixel detector: The pixel detector is the innermost component consisting of silicon pixel sensor layers, which provides highly granular tracking information. The pixel detector is arranged into four concentric layers in the barrel region, and three disks in each of the two end-cap regions. The layer closest to the interaction point is the insertable B-layer (IBL) [74, 75, 76], installed in the ATLAS detector in 2014 prior to the commencement of Run 2, and is designed to provide robust and precise track reconstruction. The IBL consists of 280 pixel modules, where pixel sensors of size $50 \times 250 \mu\text{m}^2$ are used. The remaining pixel layers are comprised of sensors with an average pixel size of $50 \times 400 \mu\text{m}^2$. The resolution of a single hit is about $12 \mu\text{m}$ in the $r - \phi$ plane, and $115 \mu\text{m}$ in the z -plane (which reduces to $72 \mu\text{m}$ for the IBL). In total around 80 million read-out channels are present in the pixel detector. On average, four hits in the pixel detector would be left by a traversing charged particle.

Semiconductor tracker: The SCT is made of 4088 silicon strip modules arranged in four concentric barrel layers and nine end-cap disks per side, each comprising of single-sided silicon micro-strip sensors. One module consists of two single-sided sensors glued back-to-back with a stereo angle of 40 mrad to obtain additional particle trajectory information; a charged particle on average consequently leaves eight hits in the SCT. The distance between adjacent strips (*pitch*) is $80 \mu\text{m}$ for the barrel sensors, and between $56.9 \mu\text{m}$ and $90.4 \mu\text{m}$ in the end-cap regions. The barrel layers provide coverage up to $|\eta| < 1.4$; the end-caps complete the coverage up to $|\eta| = 2.5$. The intrinsic hit resolution of the strip sensors is $17 \mu\text{m}$ in the $r - \phi$ plane, and $580 \mu\text{m}$ in the z -direction.

Transition radiation tracker: The TRT is the final sub-detector of the ID, which occupies the space between $R = 554 \text{ mm}$ and $R = 1082 \text{ mm}$ in the barrel region. This tracker consists of 350,848 gas-filled straw-like tubes, each 4 mm in diameter, with an anode wire (comprised of 99.95% tungsten with a gold plating) running through the centre. The wire is kept grounded, while the walls of the wire (comprised predominantly of a polyimide film) are placed at a -1.5 kV bias voltage. The straws were initially filled a Xenon gas mixture, which has subsequently been replaced due to irreparable leaks in some channels with a cheaper Argon mixture. Transition Radiation (TR) occurs when charged particles with a Lorentz factor greater than 10^3 (so highly relativistic), *transitions* between materials with dielectric constants. As such, the space between the gaseous straws is filled with polymer fibres and foils in the barrel and end-cap region respectively. The increase in readout signal induced by the traversing particles assists in discriminating between pions and electrons. This forms an important step in the electron identification procedure, up to an energy of 200 GeV . The barrel region of the TRT consists of up to 73 layers of straws, each 144 cm in length. The end-cap region consists of 160 planes of straws which are arranged perpendicular to the beam pipe; each straw is 37 cm in length [77]. The intrinsic resolution per straw is $130 \mu\text{m}$ per straw (in the $r - \phi$ plane) which although is significantly worse than the inner silicon trackers, a charged particle on average will register 36 hits in the TRT compared to the 4 or

8 hits left in the pixel detector or SCT respectively. The TRT provides tracking information out to $|\eta| < 2.0$, and requires charged particles to have a minimum transverse momentum of 0.5 GeV.

A cross-sectional view of the ID layers in the barrel region is shown in Figure 4.11, where an example of a particle track passing through the detector layers is depicted by the red line. The minimum p_T a particle must have to be reconstructed using hit measurements in the ID is 0.5 GeV. The momentum resolution of a general tracking detector is given by:

$$\frac{\sigma_{p_T}}{p_T} = a \cdot p_T \oplus b; \quad (4.7)$$

the a term captures the corresponding resolution of a curvature measurement, while the constant term b quantifies the affect due to multiple Coulomb scattering. Summing the terms in quadrature is indicated by the $\oplus$ symbol. Upon construction, the momentum resolution of the ID was $\sigma_{p_T}/p_T = 0.05\%p_T[\text{GeV}] \oplus 1\%$.

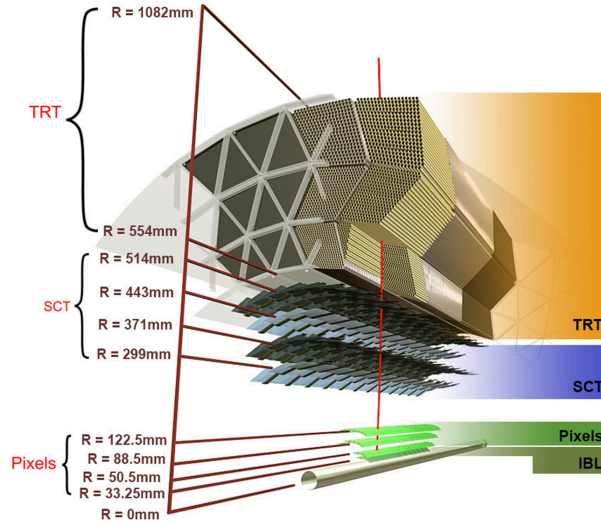


Figure 4.11: Cross-sectional slice of the ID, as used during the Run 2 ATLAS data-taking period. The distance out from the interaction point, for each sub-component, is detailed on the left side of the diagram [78].

4.4.3 Calorimetry system

Following the ID, the ATLAS calorimetry system provides energy and direction measurements of charged and neutral particles, specifically hadrons, electrons and photons, based on their energy deposits. There are three sub-systems of the ATLAS calorimetry system, each making use of their own specific technology: the EM calorimeter, the hadronic calorimeter (Had), and the forward calorimeter (FCal). This entire system is shown in Figure 4.12, where each of the sub-systems are labelled according to their barrel and end-cap sections. The EM calorimeter provides coverage

within $|\eta| < 3.2$, the Had calorimeter up to $|\eta| < 3.9$, and the FCal instead between $3.1 < |\eta| < 4.9$.

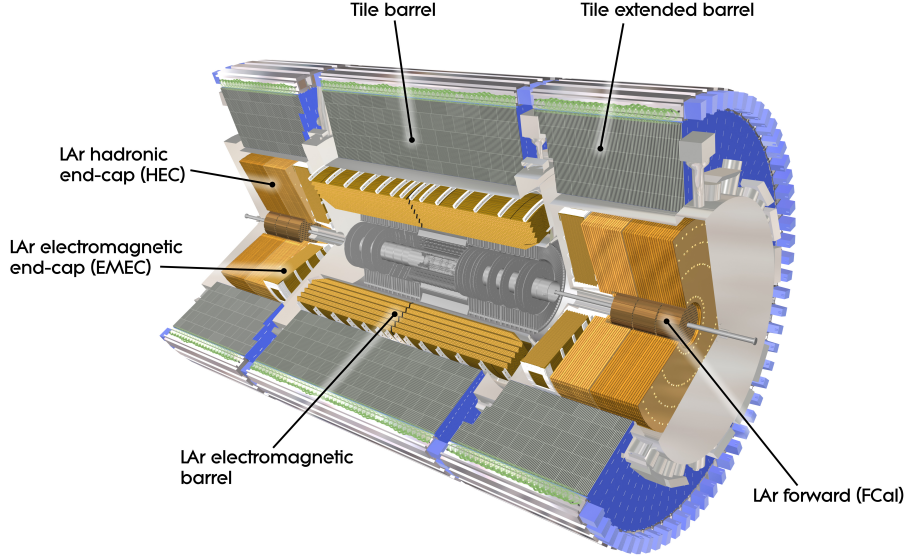


Figure 4.12: A cross-sectional view of the ATLAS calorimetry system, where the sub-systems are labelled in both the barrel and end-cap regions. The gold coloured components have a liquid argon active medium [77].

A conceptual introduction to how calorimeters work will be firstly outlined, followed by a more in depth description of this specific sub-system given the pertinence to the analysis presented in this thesis, particularly the EM calorimeter as it is used to measure the deposited energy and direction of photons.

Introduction to calorimetry: A calorimeter measures the energy deposits of a particle as it traverses and interacts with the detector material. As a particle enters the calorimeter layers, this incident particle interacts with the calorimeter material and produces secondary particles which then themselves interact with the detector material and so on (known as a *shower*). In this way, a cascade of secondary particles is produced which is measured by the detector as energy deposits. This shower continues until the particles energies are so low that they are absorbed by the material. The energies are typically measured either by scintillating material which detects light produced by the secondary particles, or by the charge induced through the particles ionising the gas or liquid detector medium.

In general, calorimeters can be classified into one of the following types:

1. **Electromagnetic:** An *electromagnetic* calorimeter is one that specifically measures electromagnetic showers, meaning interactions involving electrons, positrons and photons. An

incident photon will interact with the detector material via pair production, while an electron will undergo electron bremsstrahlung, meaning it will radiate energy in the form of photons. These two processes feed each other and so the shower continues, until the energy drops below a threshold known as the *critical energy*, E_c , defined by:

$$E_c = \frac{610 \text{ MeV}}{Z + 1.24}, \quad (4.8)$$

with Z being the atomic number of the calorimeter material. This critical energy is defined similarly for energy loss via either photon pair production or bremsstrahlung, and is also independent of the detector material being liquid or solid. An important parameter to consider when designing a calorimeter is the shower *depth*, which depends on the critical energy as:

$$L_{EM}(95\%) \approx \ln\left(\frac{E_0}{E_c}\right) + C_j + 0.08 \cdot Z + 9.6[X_0], \quad (4.9)$$

where E_0 is the incident particle's energy, $C_j = +0.5$ (-0.5) if the incident particle is a photon (electron). $L_{EM}(95\%)$ quantifies the length of calorimeter required in order to contain 95% of the shower's energy, defined in units of radiation length, X_0 . The radiation length is a property of the material itself, and represents how much material is required for an electron to lose all of its energy, except for a factor $1/e$. This property is defined in terms of the material's atomic number, Z and the mass number A [79]:

$$X_0 = \frac{716.4[\text{g cm}^{-2}] \times A}{Z(Z + 1) \times \ln(287/\sqrt{Z})}. \quad (4.10)$$

The critical energy, radiation length, and shower depth properties for liquid Argon (LAr) and lead (Pb) are given in Table 4.2. These two materials are both used in the ATLAS calorimeter.

Detector material	E_c [MeV]	X_0 [cm]	$L_{EM}(95\%)$ [cm]
LAr	32.84	14	260
Pb	7.43	0.56	15

Table 4.2: Critical energy, radiation length, and shower depth for liquid Argon (LAr) and lead (Pb) as the detector material. To calculate the radiation length, an initial electron energy of $E_0 = 100$ GeV has been assumed.

2. **Hadronic:** A *hadronic* calorimeter aims to measure showers which involve hadrons, for example neutrons or protons. A hadronic shower involves two components (unlike the EM shower which has only one): firstly there is an electromagnetic component, followed by the hadronic one. The electromagnetic shower is initiated by π^0 or η decays into photons, and accounts for anywhere between 30% and 60% of the hadronic shower's total energy. The second component is hadronic, and can consist of many strong process for example

the emission of slow neutrons, or nuclear spallation. Some of the hadronic processes can involve a component of *missing* energy, meaning the energy released was not measured by the detector, for example due to the release of the nuclear binding energy. This can account for up to $\sim 40\%$ of the total energy of the shower's non-electromagnetic component. The nuclear interaction length, λ , of a hadronic particle quantifies the mean distance travelled before undergoing a nuclear interaction, defined by:

$$\lambda \approx 35 \cdot A^{1/3} [\text{g cm}]^{-2}. \quad (4.11)$$

The total shower length of a hadronic shower is parametrised in terms of λ as:

$$L_{Had}(95\%) = 0.2 \cdot \ln(E) + 0.7 + 2E^{0.13}, \quad (4.12)$$

where E is the energy of the incident particle in GeV. Considering a 100 GeV incident pion, the interaction length and shower length for a hadronic shower are listed in Table 4.3, considering either LAr or Pb detector material. Comparing the interaction length λ of a hadronic

Detector material	λ [cm]	$L_{Had}(95\%)$ [cm]
LAr	85.77	450
Pb	17.59	90

Table 4.3: Interaction length and shower length properties when considering LAr or Lead (Pb) as the detector material. To calculate the hadronic shower length, a $E = 100$ GeV incident pion has been considered.

shower, with the radiation length X_0 of an electromagnetic shower, λ is much larger for a 100 GeV pion initiated hadronic shower, compared to a 100 GeV electron induced electromagnetic shower. This consideration is accounted for in the detector design by placing the electromagnetic calorimeter inside (closer to the interaction point than) the hadronic calorimeter. Hadrons hardly lose any energy in the EM calorimeter, whilst electrons and photons will lose energy and be stopped by the hadronic calorimeter (if they make it that far).

For any type of calorimeter, one further important parameter worth highlighting is the energy resolution which is used as a metric to quantify the calorimeter's performance. The energy resolution, $\sigma(E)/E$, is defined by:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (4.13)$$

where a is the stochastic term which parametrises statistical fluctuations of the shower's development, the b term parametrises electrical noise deriving from the read-out electronics, and c is a constant term which captures calibration uncertainties due to the electronics, detector non-uniformities as well as alignment uncertainties. The a (c) term is what limits the calorimeter's

energy resolution at low (high) energies.

In addition to calorimeters being classified as either electromagnetic or hadronic, they can also be defined as either a homogeneous or sampling calorimeter, depending on how they're designed to measure the shower. ATLAS only uses *sampling* calorimeters which, unlike homogeneous calorimeters, are not specifically designed to measure the energy of the entire shower. In this case, two alternating materials are used; one that initiates and produces the shower, this is called the *passive* material, and another to provide the measured signal, known as the *active* material. In this way, the chosen materials can be more appropriately targeted for their specific purpose. There is one disadvantage of sampling calorimeters though which is that some energy deposits may occur in the material which does not create a signal, and thus is not measured.

The size and material chosen for the calorimeter is an important consideration. It depends on the intended use of the calorimeter, meaning which specific particle types and energy range it intends to measure. The ATLAS detector consists of both electromagnetic and hadronic calorimeters; the details of the ATLAS calorimetry system will be outlined below.

ATLAS electromagnetic calorimeter: The ATLAS EM calorimeter [80, 81] is the sub-detector surrounding the ID. It is a sampling calorimeter, with 2 mm layers of liquid argon (and copper electrodes) as the active material, and lead as the absorbing material. Liquid argon is chosen as the active detector medium for this calorimeter due to its physical properties, namely its intrinsic hardness and stability over time. Layers of lead with different thickness, ranging between 1.1 mm to 2.2 mm, are glued to sheets of stainless steel which provides mechanical support. The lead absorber layers and the electrodes are folded into a so-called *accordion* geometry, shown in Figure 4.13, which aims to avoid gaps in the readout system, and achieve full ϕ coverage. The radiation length varies between $22 X_0$ and $24 X_0$ in the barrel and end-cap regions respectively, which sufficiently contains the electromagnetic showers. A typical photon shower will have a radiation length between 6 to $24 X_0$, corresponding to the second sampling layer. The granularity of this middle layer is $\Delta\eta = 0.025$, and has been optimised to contain photon showers with energies less than 50 GeV.

The EM calorimeter in total is 6.65 m long with an outer radius of 2.25 m. Geometrically, the calorimeter in the barrel region is divided into two coaxial cylinders, which have a small gap at $z = 0$, allowing for particle detection up to $|\eta| < 1.48$; the two end-caps cover the range $1.38 < |\eta| < 3.2$. The calorimeter consists of about 180,000 cells in total, with different $\delta\eta \times \delta\phi$ dimensions according to their location. Four layers consisting of different granularities are defined, as shown in Figure 4.13b. The innermost layer is the *presampler* consisting of a thin (1.1 cm) layer of LAr; *Layer 1* (L1) is the first accordion geometry layer which used very finely segmented cells in $\Delta\eta$ to discriminate between $\pi^0 \rightarrow \gamma\gamma$ decays and an incident photon; *Layer 2* (L2) is next and measures most

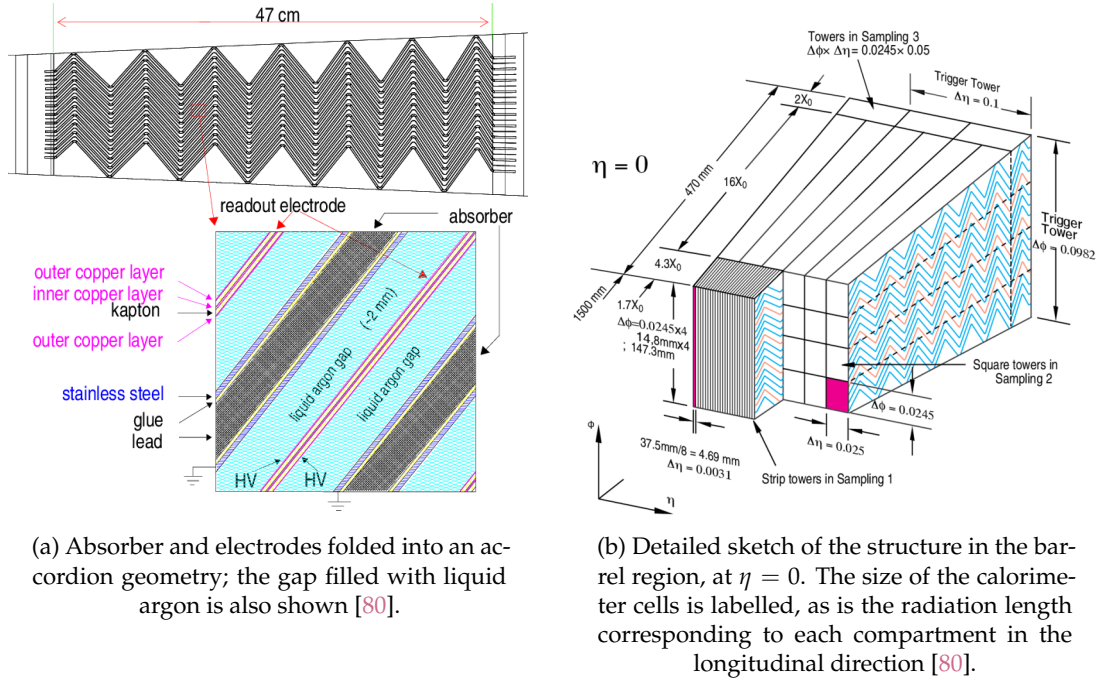


Figure 4.13: Diagrams of the ATLAS electromagnetic calorimeter accordion (4.13a) and barrel cell (4.13b) geometry.

of the energy deposits of the shower; *Layer 3* (L3) is only $2X_0$ thick, and being the final layer it aims to estimate leakage of the shower into the hadronic calorimeter.

The energy resolution of the EM calorimeter is given by equation 4.14, where the a sampling term depends on η and is typically between 8% to 11%, while c is below 0.7%. The b noise term is around 400 MeV and deemed negligible.

$$\frac{\sigma(E)}{E} \lesssim \frac{11\%}{\sqrt{E}} \oplus 0.7\% \quad (4.14)$$

ATLAS hadronic calorimeter: The ATLAS hadronic calorimeter [80, 82], for the measurement of energy deposits resulting from hadronic showers, surrounds the EM calorimeter and is cylindrical in shape measuring a total of 11.5 m long with an external radius of 4.2 m and covering a pseudorapidity up to $|\eta| < 3.9$. The hadronic calorimeter is a sampling calorimeter, and is split into barrel and end-cap regions. The *tile*, and *extended barrel* calorimeters cover the central region ($|\eta| < 1.7$); the absorber material used is steel, and the active material is scintillating tiles. The two sides of the tiles are read out into two photomultiplier tubes by wavelength shifting fibres, and each tile is a self-supporting structure composed of 64 modules. The *hadronic* end-cap covers the range $1.5 < |\eta| < 3.2$, and makes use of copper plates as the passive absorbers, with LAr as the active medium.

In total the hadronic calorimeter has a 11λ total thickness, and the nominal energy resolution is:

$$\frac{\sigma(E)}{E} \approx \frac{50\%}{\sqrt{E}} \oplus 3\%, \quad (4.15)$$

for the barrel and end-cap regions. The noise term is negligible.

ATLAS forward calorimeter: The ATLAS forward calorimeter [80, 83] (FCal) is a sampling calorimeter providing energy deposit measurements in the very forward pseudorapidity region, corresponding to $3.1 < |\eta| < 4.9$, which is especially impactful for missing transverse energy, and forward jet measurements. The active medium is LAr, chosen due to its high radiation tolerance. The absorbing medium is copper in the first section, and tungsten in the second two sections. Each of the three sections consist of a metal grid of longitudinal rods. The rods, and the gaps between the rods, are filled with LAr. The nominal energy resolution for the FCal is:

$$\frac{\sigma(E)}{E} \approx \frac{100\%}{\sqrt{E}} \oplus 10\%, \quad (4.16)$$

where the noise term is negligible.

4.4.4 Muon spectrometer

The outermost component of the ATLAS detector is the muon spectrometer (MS) [84], which is responsible for muon identification and providing muon momentum measurements for muons with an energy up to a few TeV. Muons typically make it through all of the detector layers, and leave the ATLAS detector before they decay given their mean lifetime is $2.2\mu\text{s}$. Since they are charged particles, muons leave hits in both the ID and MS and thus obtain tracking information from these two sub-detectors. Muons are deflected in the η direction as they traverse through the detector layers due to the toroidal magnetic field.

As for other sub-detectors, the MS is geometrically divided in barrel and end-cap regions. The barrel MS is comprised of three cylindrical shells surrounding the beam axis at radii of 5, 7.5 and 10 m. The two end-cap components of the MS are made of four large wheels that sit perpendicular to the beam (z) axis at distances of roughly 7.4, 10.8, 14, and 21.5 m from the interaction point. Monitored drift tube chambers are used to be able to precisely measure muon momentum; these cover the range $|\eta| < 2.7$. The innermost end-cap region of the MS uses cathode strip chambers in the range $2.0 < \eta < 2.7$. A combination of resistive plate chambers in the barrel ($|\eta| < 1.05$) and thin gap chambers are used in the end-caps ($1.05 < \eta < 2.4$).

4.4.5 Trigger and data acquisition system

During the Run 2 data-taking period, proton bunch collisions occurred every 25 ns, corresponding to a collision frequency of 40 MHz. Given an event size is $\mathcal{O}(1 \text{ MB})$ on average, the total data rate would be $\sim 40 \text{ TB/s}$ which is too large to be collected and stored, thus choices are required to reduce the size to a more realistic and manageable amount. ATLAS achieves this through using a sequence of trigger systems [85], which aim to retain the designated events of interest, and discard the abundance of processes which are not considered useful.

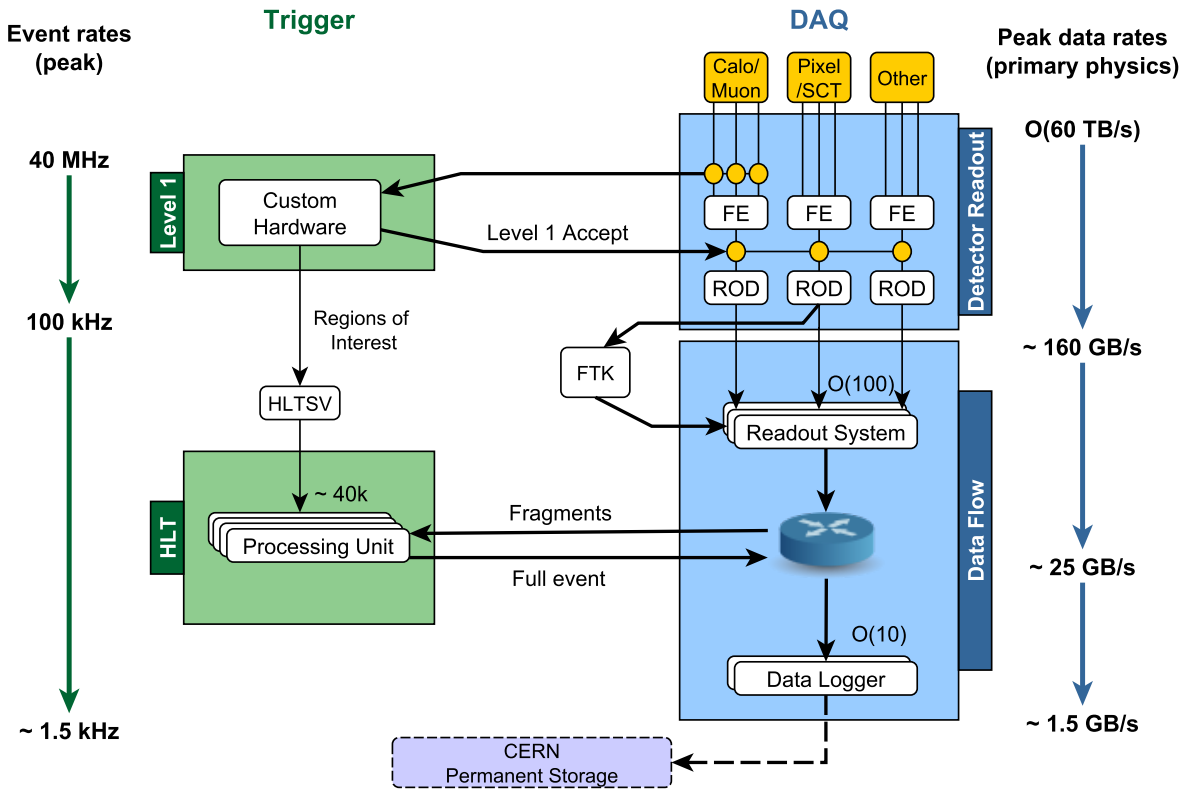


Figure 4.14: Labelled diagram of the ATLAS data acquisition and trigger systems during the Run 2 (2015 to 2018) data-taking period [86]. The event rates at each stage are written on the left; the data rates are listed on the right.

A diagram depicting an overview of the data flow is presented in Figure 4.14. Efficient and reliable algorithms are used to identify which events contain an interesting signature, and hence should be retained for physics analyses. The two main components of the trigger system are as follows. The level one (L1) online hardware trigger uses a coarse set of information obtained in the calorimeters, forward detectors and the MS to look for initial evidence of, for example, potentially interesting high p_T events or the presence of missing transverse energy. Using this information, several so called regions of interest (RoIs) are defined which is information passed on to the subsequent trigger system for further scrutiny. The L1 trigger reduces the event rate

from 40 MHz to about 100 kHz, with a processing time of $\sim 2.5 \mu\text{s}$.

The high level trigger (HLT) is a software-based trigger that uses processing farms consisting of up to 40,000 dedicated CPU cores. The HLT receives information from the L1 trigger, such as the defined RoIs for each event, which are then used to make more detailed selections on which events want to be retained. Unlike the L1 trigger, the HLT is able to use information from all detector components in its decision making process and attempts to perform a more offline-like reconstruction for each event. The HLT reduces the rate from 100 kHz to ~ 1.5 kHz, with an average processing time around 4 s. Only events which pass the high level trigger are saved offline for physics analysis.

Data collected by the ATLAS detector is then passed through the reconstruction algorithms, in order to identify which physics processes have been recorded and what particles are present in the event. The particle reconstruction, identification and subsequent calibration that is required in order to use the events for physics analyses is presented in [Chapter 5](#).

5 | Particle reconstruction with ATLAS

Particles produced by colliding protons traverse and interact with the ATLAS detector material. The raw detector information recorded must be converted into so-called *physics objects*, which can then be used to perform analyses. This is achieved through dedicated reconstruction, identification and calibration algorithms, to obtain reconstructed *physics objects* like electrons and photons.

This chapter provides an overview of how the ATLAS detector is used to reconstruct, identify and calibrate the physics objects of specific importance to the analysis presented in this thesis. In particular, focus is placed on describing the algorithms used for identifying photons given these are the final state particles used to perform the presented Higgs boson width measurement in the $H \rightarrow \gamma\gamma$ decay channel. Physics object definitions usually begin with high-level detector information such as tracks and vertices in the ID, and clusters of energy deposits in the calorimeters. The objects are built based on the expected experimental signature of different particle types. Figure 5.1 presents a cross-sectional view of the various ATLAS detector components, where the experimental signatures left by different particle types are illustrated. Particle trajectories which are invisible to the ATLAS detector components are indicated with a dashed line.

Photons, being electrically neutral, do not bend or leave signatures in the ID layers. Instead, an electromagnetic shower is induced through the photon interacting with the detector material. The photon leaves energy deposits within the EM calorimeter layers. Electrons leave similar signatures in the EM calorimeter, though they additionally leave hits in the ID that allow their charge sign and momentum to be determined. Electrons and photons are both entirely stopped by the EM calorimeter, and thus are not detected by either the hadronic calorimeter or the MS.

Neutrons, having no electric charge like the photon, also pass tracelessly through the ID. Since they are hadrons, their energy deposits occur predominantly in the hadronic calorimeter layers. This is true also for protons which additionally leave deposits in the ID.

Calorimeters stop most known SM particles with the exception of muons and neutrinos. Muons minimally interact with the detector material, and thus traverse the calorimeter layers without

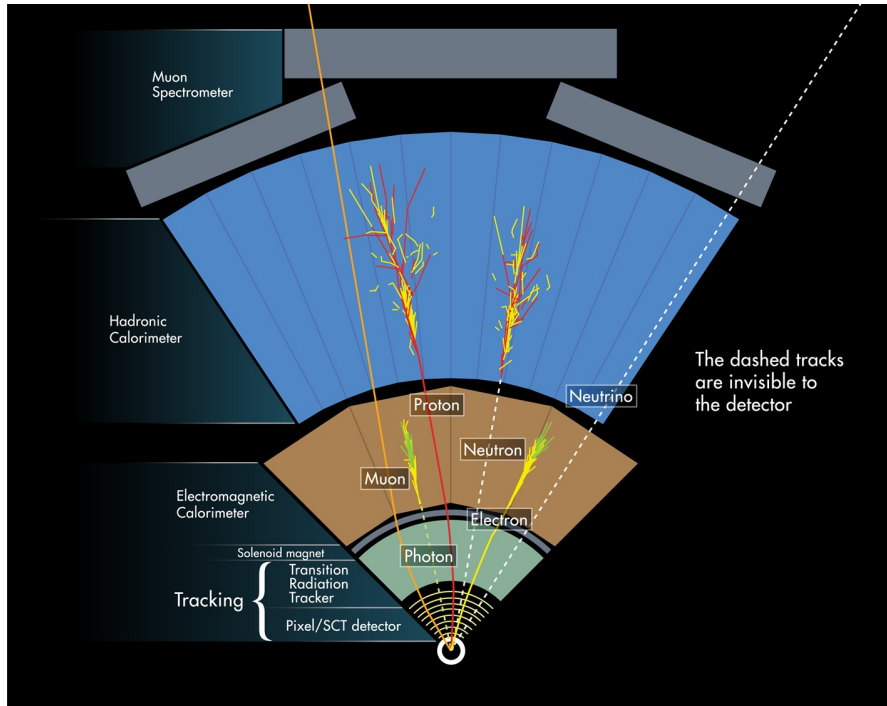


Figure 5.1: A cartoon cross-sectional view of the ATLAS detector highlighting which sub-systems are responsible for detecting different particle types [73].

showering. Given their electric charge, they leave curved tracks in both the ID, and the MS. Muons are the only particles which make it to, and are measured in the MS; they generally are not stopped entirely by the MS. Neutrinos are invisible to the ATLAS detector as they interact with matter very weakly and thus do not leave hits in any of the detector layers. Their presence is instead inferred through a lack of momentum conservation in the transverse plane when summing up the momentum of all other particles detected in a given event.

5.1 Tracks and vertices

Tracking information is crucial to the reconstruction of many particles measured by the ATLAS detector, specifically by the ID and MS. This section will focus on the procedure used to reconstruct tracks in the ID only. In addition to identifying charged particle trajectories, the precise reconstruction of charged particle tracks is also used as input to identify other objects, such as the primary vertex and for pile-up removal. Hits recorded in the pixel and SCT detectors, as well as drift circles in the TRT, are input into the track reconstruction algorithm. There are two algorithm procedures which are used. The ‘inside-out’ algorithm is called as such since it begins with information recorded in the pixel layers, and adds sequentially from the outer layers, first using information from the SCT, and then finally the TRT. The primary intention of this algorithm is to efficiently reconstruct tracks produced in hard-scattering events. The second algorithm instead is the ‘outside-in’ method, which as the name suggests, begins from the TRT measurements

and includes hits from the silicon detectors afterwards. This method is predominantly used for events containing longer lived particles involving b or c hadrons. Tracks are entirely defined by five parameters, with respect to a reference point; the transverse, d_0 , and longitudinal, z_0 impact parameters, the polar angle relative to the track's momentum vector at the reference point, θ , the azimuthal angle, ϕ , and the charge to momentum ratio, q/p . A visual representation of these parameters is shown in Figure 5.2. Tracks that are to be used for physics analyses must lie within the ID fiducial volume, $|\eta| < 2.5$, and pass a minimum p_T threshold of $p_T > 0.5$ GeV.

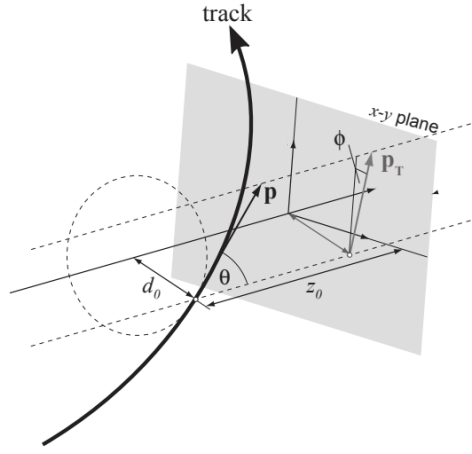


Figure 5.2: Illustration of the track parameters.

A vertex is defined to be the intersection point between tracks. The *primary* vertex corresponds to the main pp interaction in a given bunch, and is usually identified through a vertex finding and fitting algorithm [87, 88]. Tracks are iteratively added to a starting vertex seed, if they align with the position of that vertex, and these candidate tracks are weighted according to their relative compatibility. Tracks not compatible with a given candidate vertex then become a seed for another vertex. Ultimately the primary vertex is defined to be the vertex with the largest sum $\sum_i p_T^i$ over all tracks, i , associated with that vertex. As it turns out, this method does not work well for identifying the primary photon vertex corresponding to di-photon events, and so an alternate algorithm is used specifically to identify the diphoton primary vertex. More details on the definition of the diphoton primary vertex will be described in section 6.3.1.

5.2 Electron and photon reconstruction

The accurate measurement of electrons and photons plays a critical role in the success of fundamental particle property measurements, such as the analysis presented in this thesis. The reconstruction of energy deposits in the EM calorimeter are used to identify and distinguish between electrons and photons, along with tracks left by electrons in the ID. Tracks left in the ID are exploited to differentiate between the following objects: *electrons* are characterised by tracks left in

the ID matched to energy deposits in the EM calorimeter; *converted photons* are photons that have interacted with the ID material and subsequently converted to an e^-e^+ pair, identified through matching with either tracks in the ID or a conversion vertex (or vertices); *unconverted photons* are characterised purely by energy deposits left in the EM calorimeter, and are not matched with any tracks or vertices in the ID.

The offline reconstruction of electrons and photons is based on the use of *superclusters*, which are defined as dynamic, variable-sized clusters. A cluster is simply a collection of energy deposits measured in the EM calorimeter. While proving stable against pileup, using dynamic superclusters has the added benefit of being able to vary in size as required to recover, for example, low-energy clusters due to bremsstrahlung photons or electrons clusters originating from photon conversions [89].

The algorithm used to reconstruct electrons and photons is illustrated in Figure 5.3. This algorithm can be categorised into three sequential steps, which are indicated on the right hand side of the diagram. Firstly the tracks and clusters used as inputs to the algorithm are prepared, and this will be described in section 5.2.1. Building the electron and photon superclusters then follows, each in parallel, which will be outline in section 5.2.2. Section 5.2.3 will describe how finally the electron and photon objects are prepared for use in physics analyses.

5.2.1 Topo-clusters

Topo-clusters are the starting point for electron and photon reconstruction. The algorithm used for topo-cluster reconstruction [91, 92], commences by defining *proto-clusters* of energy deposits in the electromagnetic and hadronic calorimeters. The first step is to calculate the significance quantity, $\zeta_{\text{cell}}^{\text{EM}}$, defined to be the ratio between the cell's energy and the expected cell noise:

$$\zeta_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}}, \quad (5.1)$$

whereby the specific cell initiating the proto-cluster, known as the seed, must have $|\zeta_{\text{cell}}^{\text{EM}}| \geq 4$. Note here that cells in all of the calorimeter layers are considered with the exception of the Pre-sampler and Layer 1 cells. Once the initial seed is defined, any neighbouring cells that satisfy $\zeta_{\text{cell}}^{\text{EM}} \geq 2$ are added included in the proto-cluster. The final step is to also add all nearest-neighbour cells, with no minimum energy requirement, to those cells included in the first two steps of the procedure. This algorithm is commonly referred to as the "4-2-0" method, due to the sequence of noise thresholds that's used.

Since the topo-clustering algorithm uses proto-clusters from both the EM and Had calorimeters, the identification of EM showers is achieved by requiring the fraction of EM energy to be at least

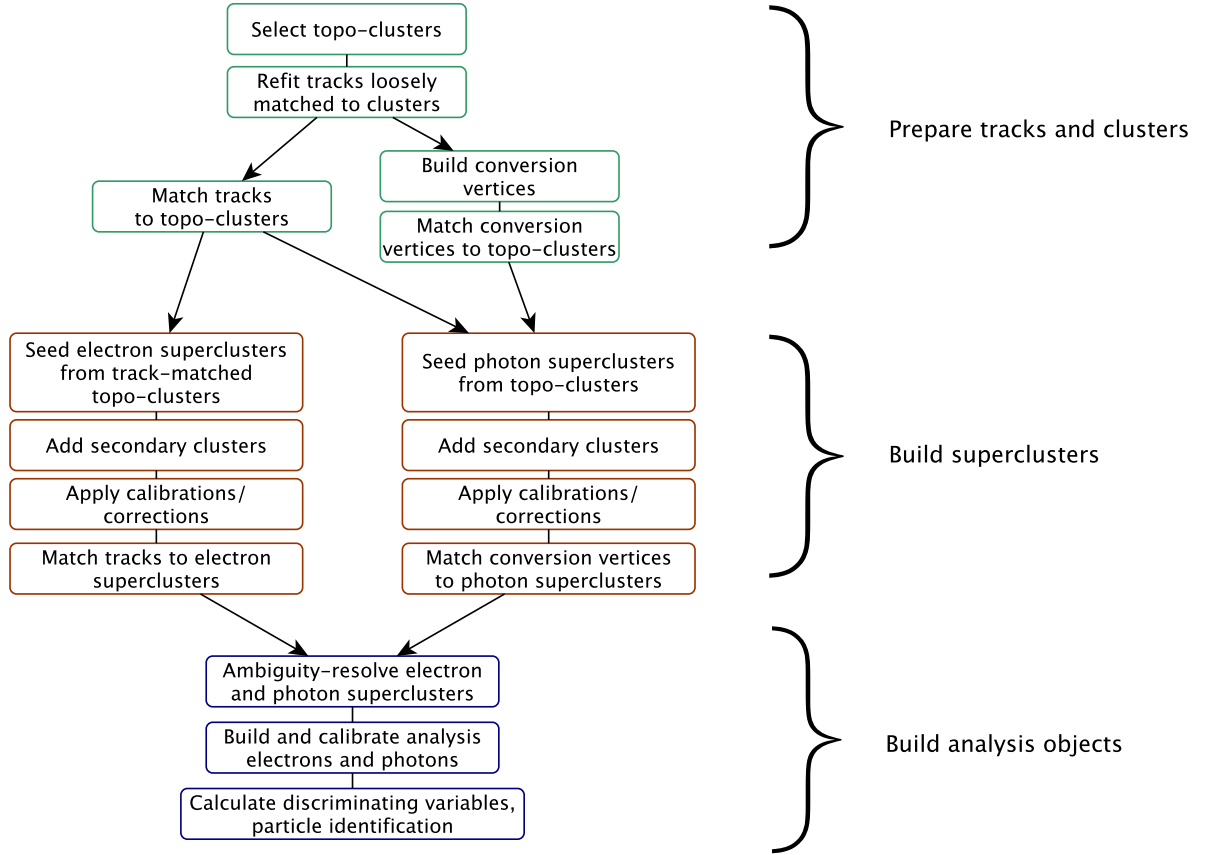


Figure 5.3: Algorithm workflow used to reconstruction electrons and photons [90]. The steps undertaken to define electron and photon objects proceed in parallel.

0.5 for the cluster to be classified as an electromagnetic shower. This fraction is defined as:

$$f_{\text{EM}} = \frac{E_{L1} + E_{L2} + E_{L3}}{E_{\text{cluster}}}. \quad (5.2)$$

In such cases, the hadronic cells are removed. The reason this specific criteria was chosen is demonstrated in Figure 5.4, which nicely illustrates that this value of 0.5 is able to remove a significant fraction of pile-up clusters ($\sim 60\%$), whilst having very little impact on correctly identifying the ‘real’ electron topo-clusters. To be considered as a topo-cluster, the EM energy must be larger than 400 MeV; these are henceforth labelled as EM topo-clusters.

The algorithm identifies potential matches between clusters and tracks in the ID which are extrapolated to the calorimeter. In cases where a reconstructed track matches a cluster, the object is classified as an electron candidate, and the track is then re-fitted to account for bremsstrahlung. A cluster is said to *match* a track if it’s within $|\Delta\eta| < 0.05$ from the cluster, and satisfies the requirement $-0.10 < q \cdot (\phi_{\text{track}} - \phi_{\text{clus}}) < 0.05$, where q is the track’s reconstructed charge. The reason this latter requirement is asymmetric in nature is due to the potential situation where a track has

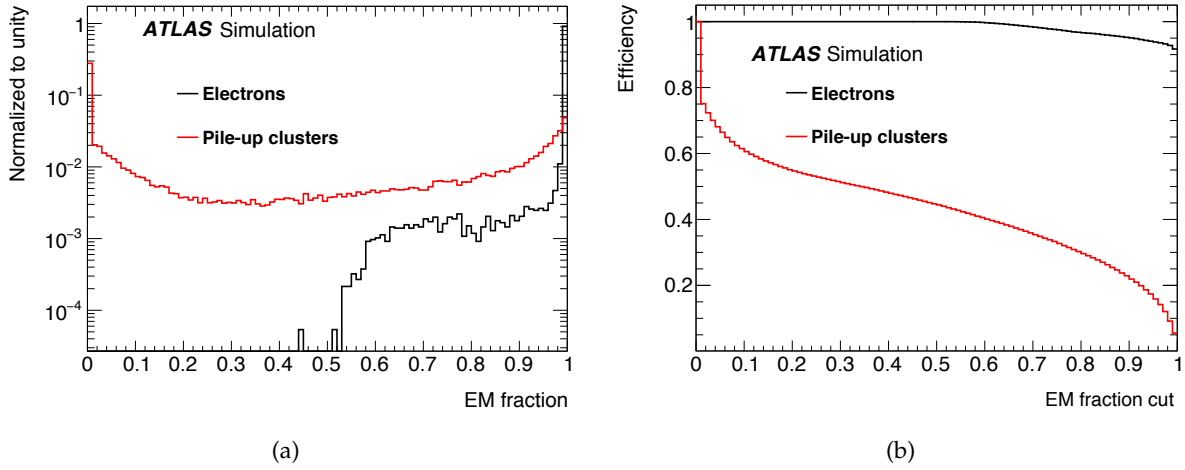


Figure 5.4: 5.4a Distribution of the EM energy fraction, f_{EM} , and 5.4b the reconstruction efficiency as a function of f_{EM} , when comparing pile-up clusters (in red) with true electron clusters (in black) [90].

missed some energy from radiated photons that has been measured by the clusters. In the absence of such a matching track, the cluster is instead classified as a photon candidate. Should a cluster match tracks compatible with the photon conversion process, $\gamma \rightarrow e^+e^-$, the event is deemed to be a converted photon candidate.

5.2.2 Superclusters

There are two independent procedures for reconstructing electron and photon superclusters, though they both have two stages. Firstly, seed supercluster candidates are identified by testing out the EM topo-clusters and assessing their suitability; using these results, EM topo-clusters near to the aforementioned seed candidates are defined as *satellite* clusters if they meet proximity related selection criteria, at which point they're added to the supercluster candidate to form the final *supercluster*.

The EM topo-clusters are sorted by decreasing E_T (EM energy), and are tested one by one for use as supercluster seeds. A topo-cluster must have $E_T > 1$ GeV and be matched to a track with ≥ 4 hits in the pixel and SCT detector layers, to be eligible as an electron supercluster seed. To be a photon supercluster seed, the cluster must satisfy $E_T > 1.5$ GeV. There is no hit or conversion vertex requirement imposed for the photon candidate. If the seed requirements are met, the satellite clusters are then found using the algorithm pictorially shown in Figure 5.5. If a cluster is within a geometry window of $\Delta\eta \times \Delta\phi = 0.075 \times 0.0125$ of the seed cluster barycentre, it is considered a satellite cluster for both electron and photon supercluster candidates. In addition, a satellite cluster is defined as such for an electron candidate if it is within $\Delta\eta \times \Delta\phi = 0.125 \times 0.300$ around the seed barycentre, and the identified best-matched track corresponds to that of the seed cluster. For photon candidates, satellite clusters are also added if their conversion vertices match that of the seed cluster's, and the tracks defining the conversion vertex consists entirely from hits

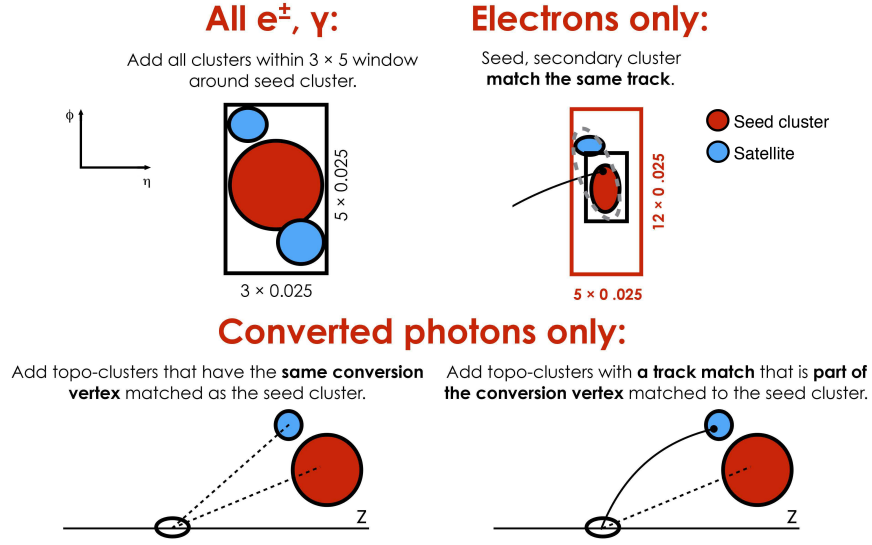


Figure 5.5: Diagram of the e^- and γ superclustering algorithm [90]. The red circles represent supercluster seeds, while the blue indicates the satellite clusters.

in the silicon trackers. These selection criteria assist in mitigating against pile-up noise, and other means of incorrectly identifying clusters not related to the original electron or photon cluster.

The seed cluster and all associated satellite clusters, then form the final supercluster by combining all cells associated to those individual clusters.

5.2.3 Electrons and photons for analysis

Once the super-clusters are built, tracks are matched to the electron superclusters, while conversion vertices are matched to the photon superclusters. This matching is defined for superclusters in the same way as for the matching to EM topoclusters, as described in section 5.2.1. Additionally, a position correction is applied and an initial energy calibration is performed. Electrons and photons for analysis are then defined. Since the electron and photon superclusters are built independently, the possibility remains that any given seed cluster could be identified as both an electron and photon. To resolve this ambiguity, the procedure defined in Figure 5.6 is followed.

Although this procedure can aid in identifying electrons that are clearly electrons (cluster with no photon conversion vertex but good tracks), or likewise for photons (no tracks), there remains some instances where this is not possible. In this case, one of each electron and photon objects are created for analysis, though each receives an *ambiguous* label, such that a final classification can be undertaken at the analysis level. In the case of electron and unconverted photon candidates, less than 10% of objects are labelled as ambiguous, whereas for converted photons it's about 35%. In standard $H \rightarrow \gamma\gamma$ analyses such as the one presented in this thesis, all ambiguous objects are

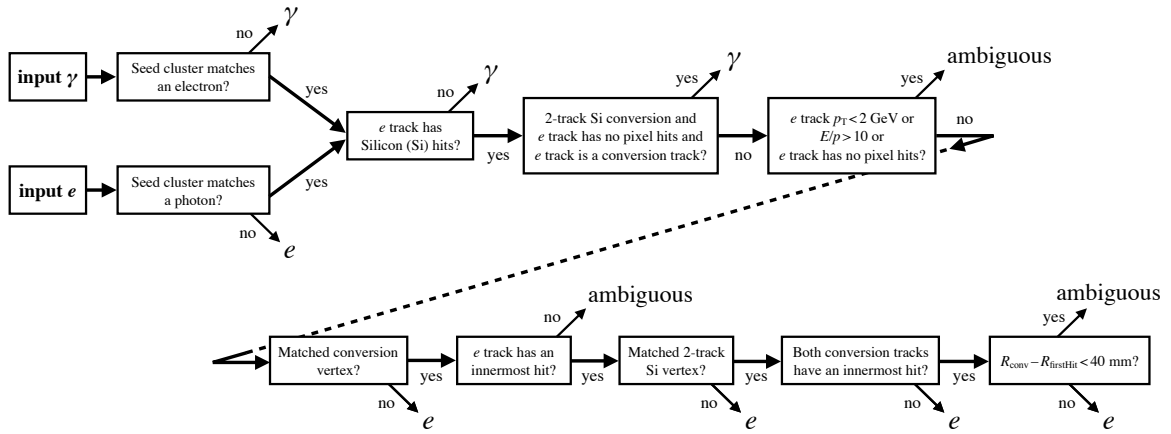


Figure 5.6: Flow chart used to resolve the cases where a particles have been initially reconstructed as both electrons and photons. If the ambiguity is resolved, only that particle is then created for analysis-level. Otherwise both an electron and photon object are created and labelled as ambiguous [90].

defined as photons so to maximise the photon reconstruction efficiency.

The reconstruction efficiencies for electrons and photons (both converted and unconverted) are shown in Figure 5.7. The photon reconstruction efficiency plots also contain a comparison between the current and previous reconstruction procedure, which used a sliding-window algorithm [92, 93, 94] to define fixed-sized clusters, instead of dynamic variable-sized superclusters as described here. Electrons with a true energy of $E_T \sim 5$ GeV have an 70% reconstruction efficiency, which increases to 95% and above when $E_T > 10$ GeV. Converted photons generally have a reconstruction efficiency of 70%, with little dependence on pile-up, decreasing by only up to 10% in the worst case towards $\langle \mu \rangle = 50 - 60$. The reconstruction efficiency for unconverted photons is much higher, remaining at or above around 90%, with a few percent mis-identified for high pile-up events.

The initial supercluster energy calibration is undertaken prior to the final track and conversion vertex matching process. Since the energy calibration depends on this final matching, the final energy calibration is done on the particles following the procedure which will be described in section 5.3. Finally, discriminating variables are defined such as cell energies and the shower shape, which are used for electron and photon identification. A detailed list of these variables can be found in [90].

5.3 Electron and photon energy calibration

An accurate determination of the electron and photon energies is required for many ATLAS physics measurements, of which determining the Higgs boson width in the $H \rightarrow \gamma\gamma$ decay channel

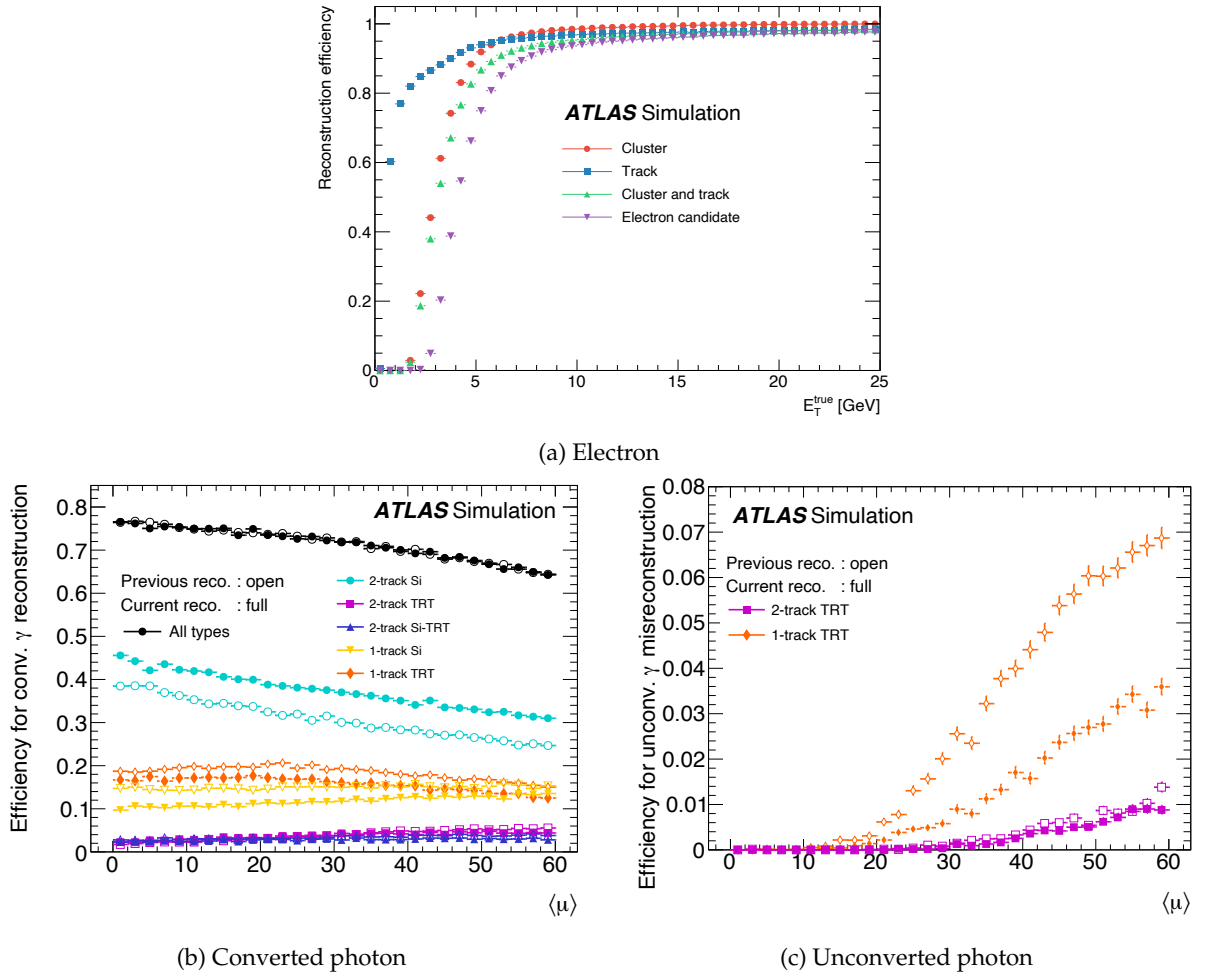


Figure 5.7: Reconstruction efficiencies for 5.7a track, cluster, cluster and track, and candidate electrons as a function of the true generated transverse energy, E_T , and for 5.7b different types of converted photons as a function of pile-up. Figure 5.7c displays the mis-reconstruction efficiency of unconverted photon types, as a function of pile-up [90].

is one. This is achieved through precisely calibrating the energies measured for electrons and photons by the ATLAS detector. The workflow followed for the energy calibration is displayed in Figure 5.8, where each step will be discussed below.

The sum of raw cluster energies which make up the supercluster, E_{raw} , as measured by the electromagnetic calorimeter cells, is the starting point for the energy calibration procedure. Since the various EM calorimeter segments vary with depth, the longitudinal layers must be independently calibrated so to correctly account for the calorimeter response since it depends on E_T . This is applied to data only, and is determined through comparing energy deposits in data with that of $Z \rightarrow \mu^+ \mu^-$ simulated events, since muons are not affected by the inactive material preceding the EM calorimeter. This procedure is known as layer *inter-calibration*, and is labelled *step 1* in the energy calibration workflow.

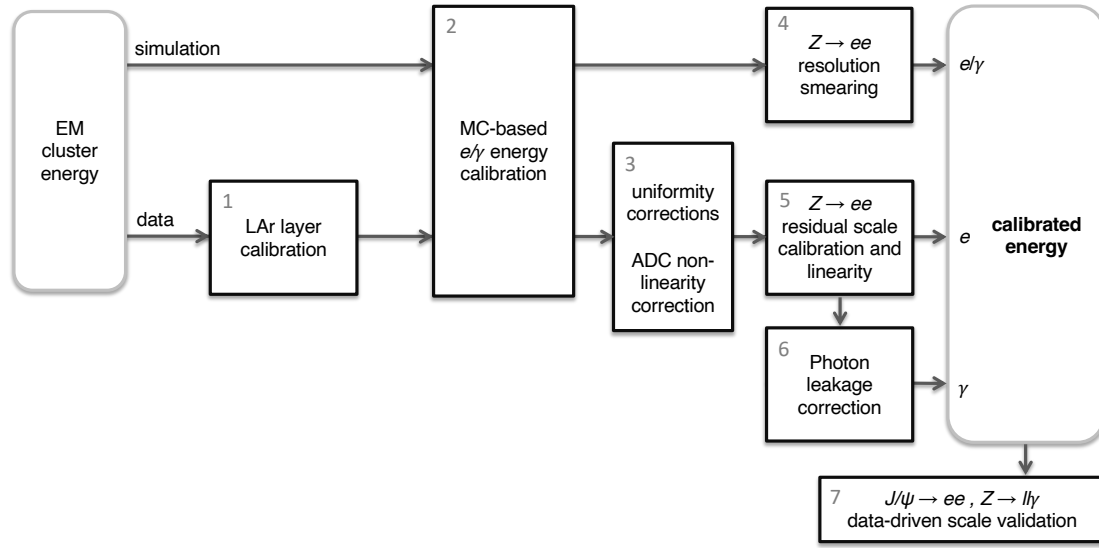


Figure 5.8: Diagram illustrating the procedure undertaken to perform and validate the electron and photon energy calibrations, for both MC simulated events (upper part of diagram) and data (lower part) [95].

The accuracy of the measured energies is limited by several effects including the finite dimension of the cluster as well as the presence of inactive material in front of and inside the EM calorimeter which inhibits the possibility of measuring the clusters energy deposits entirely. Energy loss can occur in these layers of inactive material, for example due to the inactive material between the interaction point and the first calorimeter layer; without correctly accounting such losses, the measured cluster energies would be reduced in comparison to the true energies. These effects are accounted for through the use of a MC-based multivariate regression algorithm (MVA), which uses input parameters such as the shower shape and development in the calorimeter layers, the true energies in the various layers, and η of the cell boundaries. A boosted decision tree (BDT) regression algorithm is trained to optimise the measurement of the cluster energies, which is performed independently for electron, converted photon, and unconverted photon candidates [96]. The MVA uses identified correlations between the ratio of energies $E_{\text{true}}/E_{\text{raw}}$ and the input parameters to determine a correction factor which should be applied. This factor when applied to the E_{raw} allows for the final calibrated energy to be retrieved. This MC-based energy calibration procedure is labelled *step 2*, and is applied to both MC and data.

The next step in the procedure, *step 3*, is to account for instabilities and non-uniformities in the energy response of the EM calorimeter as a function of for example the azimuthal angle, pile-up, geometric effects, and detector inefficiencies such as the dependence on read-out electronics - in particular biases induced by calibrating the LAr hardware electronics [97]. As an example, mechanical deformations of the calorimeter over time due to gravity are observed to affect the energy

response at a level of 0.1% – 0.2% in the barrel region, and around 1% in the end-cap regions. Consequently, corrections are applied to data to account for such effects. In a LAr calorimeter cell, the energy reconstruction is elicited from a linear conversion between the obtained analog-to-digital converter (ADC) counts and the corresponding current value, followed by a conversion from this current to energy. The dedicated electronics used to achieve these conversions are found to possess an inherent non-linear behaviour, where the residual difference between the actual behaviour and the expected linear behaviour is on the order of 0.3%. Corrections are derived from dedicated electronics calibration runs by studying the residuals obtained when comparing the measured ADC count with the injected current, for each individual calorimeter cell. Corrections applied in *step 3* are to data only.

After taking into account the LAr layer inter-calibration scale factors, simulation based corrections, and non-uniformities in the detector response, there is still a residual difference present between the energy scale and resolution when comparing the MC simulated events with data, which needs to be accounted for. This is achieved through studying $Z \rightarrow e^+e^-$ events where firstly corrections, α_{ij} , to the peak central position of the Z resonance is applied to the data so it matches the simulation (*step 5*). These corrections scale the invariant mass distributions according to $m_{ij}^{\text{corr}} = m_{ij}/(1 + \alpha_{ij})$ where the ij denotes different η bins for the two electrons, and $\alpha_{ij} = (\alpha_i + \alpha_j)/2$. Additionally the resolution of the $m_{e^+e^-}$ peak in data is usually found to be worse with respect to the simulation, so a correction is derived and applied to the simulation (*step 4*), as $(\sigma_m/m)_{ij}^{\text{corr}} = (\sigma_m/m)_{ij} \oplus c_{ij}$ where $c_{ij} = (c_i \oplus c_j)/2$. The correction factors for the peak position and resolution, α_{ij} and c_{ij} respectively, are defined to be those values which result in the best agreement between the simulated events and data, evaluated separately for each (i, j) category. Figure 5.9 shows the $m_{e^+e^-}$ invariant mass distribution obtained from $Z \rightarrow e^+e^-$ events for both data and simulation, after these corrections have been applied. Corrections are applied to electrons and photons in the same way, since they're assumed to originate from the inherent behaviour of the calorimeter and thus affect electrons and photons identically.

One further photon-specific correction is needed however due to the lateral shapes differences in electron and photon showers. In general, between 1% and 6% (dependent on the particle type, η and E_T) of the shower's energy is deposited outside the reconstructed supercluster. Data and simulated $Z \rightarrow e^+e^-$ and $Z \rightarrow \ell^+\ell^-\gamma$ events are used to understand the effect of this *lateral shower leakage* on the particle's energy, which is found to be less than 0.1% for electrons and so is included as a systematic uncertainty. For photons on the other hand this has up to a 3 – 4% effect depending on E_T and η , for both converted and unconverted photons. Corrections are applied to data for photon candidates, to account for these discrepancies (*step 6*).

After all above correction and scale factors have been applied, the final calibrated electron and

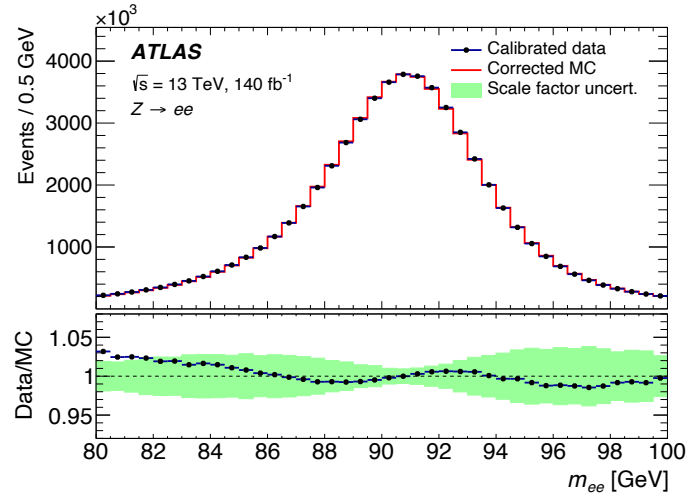


Figure 5.9: Invariant mass distribution of $Z \rightarrow e^+e^-$ events after the energy scale and resolution corrections have been applied [95]. The number of MC simulated events are scaled to match the number of observed events in data.

photon energies have been determined. The last step in the energy calibration procedure is to validate these final values (*step 7*). Low energy electron events recorded in data from the $J/\psi \rightarrow e^+e^-$ decay channel, as well as photons from $Z \rightarrow \ell^+\ell^-\gamma$ decays are used to perform this validation. The observed residual difference between data and simulated events is quantified by the residuals, α_i . The α_i values should all be close to zero if the energy calibration is correct. An example of the simultaneous shape fit to the m_{ee} invariant mass distribution from J/ψ decays, performed to extract the α_i scale factors by comparing data and simulated events, is shown in Figure 5.10a, where the total fit model is displayed by the blue line. The resulting α_i values, as a function of E_T are shown in Figure 5.10b as obtained using $J/\psi \rightarrow e^+e^-$ decays, and are all observed to be consistent with zero within the calibration uncertainty. This is also true for the α_i values obtained for validating the energy calibration of converted and unconverted photon candidates. The validation results are detailed in reference [95], as part of a comprehensive description of all steps in the energy calibration procedure.

5.3.1 Energy calibration uncertainties

There are in total 64 and 67 independent sources of systematic uncertainties for the electron and photon energy scale respectively, which make up the full systematic uncertainty model. These include effects due to the beam configuration, material present in front of and between the detector layers, as well as modelling uncertainties due to the various methodologies used to derive the numerous correction factors. Since these can have a non-negligible impact on the energy calibration, they must be accounted for in $H \rightarrow \gamma\gamma$ analyses such as the one presented in this thesis. The impact of the dominant calibration uncertainties will be presented here, while their inclusion and effect on the final Higgs boson width measurement will be summarised in section 6.8.1 as part of

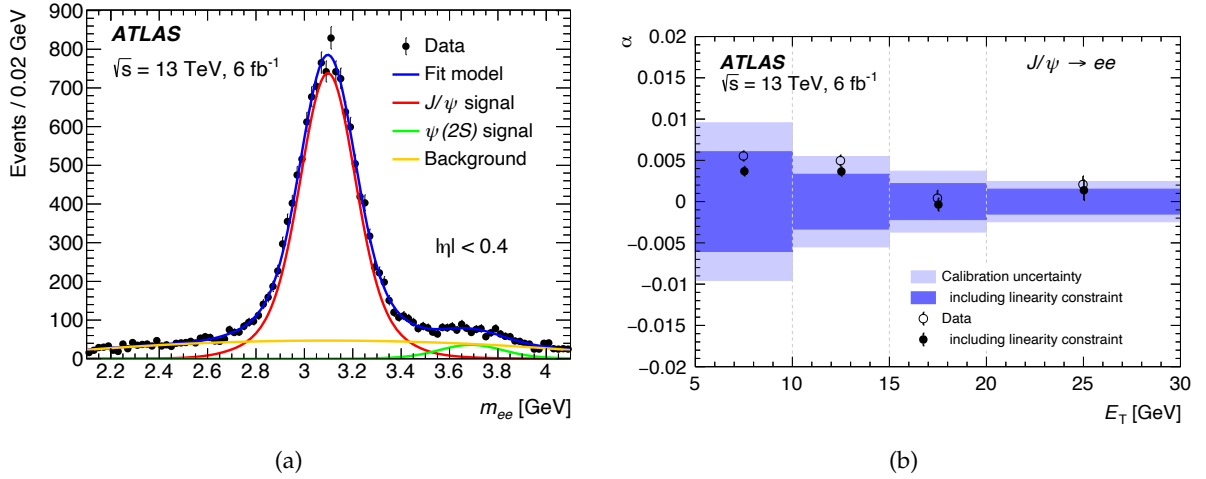


Figure 5.10: Distributions used to validate the energy calibration procedure using $J/\psi \rightarrow e^+e^-$ decays [95]: 5.10a displays the $m_{e^+e^-}$ invariant mass distribution including the fitted signal and background contributions used to obtain the residual energy scale factors; 5.10b shows the energy scale residuals, α_i , as a function of E_T .

the analysis procedure.

Figure 5.11 shows the relative magnitude of the dominant energy scale calibration uncertainties as a function of the energy, E_T , for 5.11a electrons and 5.11b unconverted photons in the more forward region where $|\eta| = 2.1$. It is expected that the relative uncertainty is at zero around $E_T \sim 40 \text{ GeV}$ for electrons, since this is where the energy scale measurement is done; the further you go from this point, the larger the uncertainty is expected to be. Aside from the total uncertainty and the global energy scale determination from $Z \rightarrow e^+e^-$, the various other individual calibration uncertainties are shown only as one-sided variations. The main contributions to the total energy scale uncertainty come from:

- $\alpha_{1/2}$: represents the intercalibration between the first and second accordion layers of the calorimeter which are split into seven $|\eta|$ regions. Although the magnitude of this uncertainty varies substantially as a function of E_T , on average the value is around 0.2% for electrons and converted photons, and 0.3% for unconverted photons;
- L1 gain (MG/HG): corresponds to the non-linearity effects in the calorimeter cell read-out specifically in layer 1 (L1) of the calorimeter, where uncertainties due to the transition between medium gain (MG) and high gain (HG) are accounted for [96]. The magnitude of this systematic is on average around 0.2% for electrons and converted photons and around 0.4% for unconverted photons, though there is a large dependence on E_T ;
- For electrons, the third largest contribution is an uncertainty accounting for lateral shower leakage, caused by a fraction of the clusters energy being outside the shape identified during the supercluster reconstruction;

- For unconverted photons, the third dominant contribution labelled ‘*conversion reco. class*’ captures the efficiency and fake rate associated with the mis-classification of a converted photon as an unconverted one.

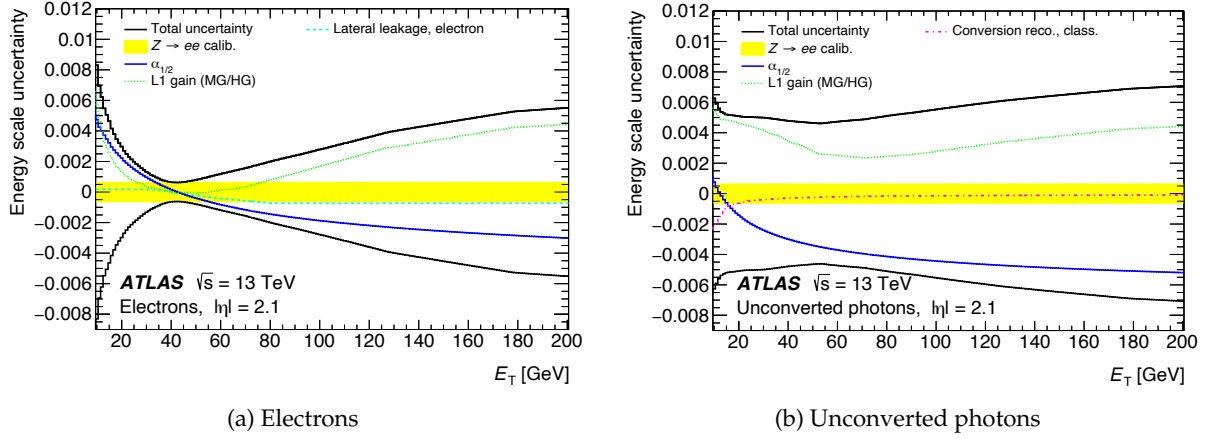


Figure 5.11: Relative energy scale calibration uncertainties, for 5.11a electrons, and 5.11b unconverted photons, with $|\eta| = 2.1$ [95]. The individual contributions to the total uncertainty are illustrated only as one-sided variations for simplicity, with the exception of the Z scale calibration.

Similarly to electrons, the dominant energy scale calibration uncertainties for converted photons are due to the L1 gain, and $\alpha_{1/2}$ where the order of magnitude of the total uncertainty is similar to that for the electron candidates, since the shower shape develops more similarly to that of an electron's.

The relative energy resolution calibration uncertainties for electrons and unconverted photons are displayed in Figure 5.12, for more central particle candidates with $|\eta| = 0.3$. The magnitude of the energy resolution uncertainty is quantified by the variation on the nominal resolution, σ , of the peak on the invariant mass distribution, indicated as δ_σ/σ . The leading contribution to the energy resolution uncertainty arises from the effects due to pile-up. Overall the relative uncertainty in the energy resolution is less than 0.1 when $E_T < 70$ GeV, which increases substantially as a function of E_T .

The calibration uncertainties achieved are on the order of 0.4% for electrons with energy $E_T \sim 10$ GeV, 0.3% for electrons with energy $E_T \sim 1$ TeV, and 0.2% for photons with $E_T \sim 60$ GeV on average. To give some context for the $H \rightarrow \gamma\gamma$ analysis presented in this thesis, the mean value of the leading and sub-leading photon energies, corresponding to the two resonant signal final state photons used in this analysis, are 125.6 GeV and 92 GeV respectively. As part of this analysis, section 6.8.1 details the procedure used to assess the impact of these systematic uncertainties on the measurement of the Higgs boson width, Γ_H . The next step in preparing the electron and photon candidates for use in ATLAS physics analyses is to apply selection criteria which aims

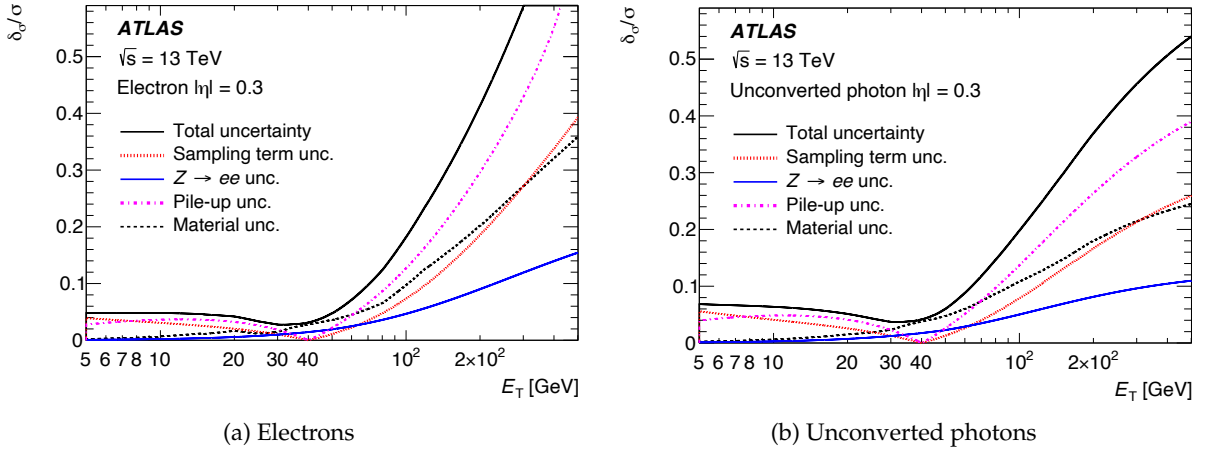


Figure 5.12: Relative energy resolution calibration uncertainties, for 5.12a electrons, and 5.12b unconverted photons, with $|\eta| = 0.3$ [95].

to reduce background contributions while maintaining a high efficiency rate for selecting real photons and electrons; this will be outlined in section 5.4 and 5.5 respectively.

5.4 Photon performance

To target events with two photons in the final state, as is the case for the $H \rightarrow \gamma\gamma$ analysis presented in this thesis, additional selections must be applied following the photon candidate reconstruction so to efficiently remove background events, typically in the form of hadronic QCD di-jets and photon-jet production, whilst retaining as real photons as possible. Given the background contributions are orders of magnitude larger than the expected cross-section of the $H \rightarrow \gamma\gamma$ signal, this procedure is of paramount importance otherwise the signal will be entirely concealed by background. This is done in two stages: firstly *identification* (5.4.1) selections are applied which aim to identify electromagnetic showers that are distinctively photon-like, followed by *isolation* (5.4.2) criteria which quantify the magnitude of energy deposits or number of tracks in the vicinity of a photon candidate. These are defined for both electrons and photons; the procedure followed for electrons will be outlined in section 5.5.

5.4.1 Photon identification

The main purpose of applying photon identification criteria is to select events containing prompt, isolated photons with high efficiency, whilst rejecting background events. The photon identification criteria is defined by a set of shower shape variables, constructed from information collected in the ATLAS calorimeters. The criteria aim to exploit the differences in shower shapes for photon showers versus jets; jets typically generate deeper (further into the calorimeter layers) and wider (larger spread in ϕ) showers compared to photons. Photon showers are usually contained

in the EM calorimeter, whilst hadronic jets deposit a significant fraction of their energy in the hadronic calorimeter. There are three photon identification criteria defined: *loose*, *medium*, and *tight*, colloquially referred to as the identification *working points*. The background rejection efficiency increases sequentially, starting with loose being the least capable. The variables used to define these three identification criteria are summarised in Table 5.1, where the last three columns indicate which variables are exploited for each of the three criteria.

Category	Name	Description	Loose	Medium	Tight
EM 1st layer	w_{s_3}	Lateral shower width determined using 3x2 strips defined by taking those surrounding strip with largest energy deposit			✓
	$w_{s_{tot}}$	Lateral shower width in total			✓
	F_{side}	Defined by $(E_7^{S_1} - E_3^{S_1})/E_3^{S_1}$; ratio of energy difference (between seven strips and three central strips) with respect to energy in three central strips			✓
	ΔE	Defined by $E_{max,2}^{S_1} - E_{min}^{S_1}$			✓
	E_{ratio}	Ratio of energy difference between the two largest energy deposits, with respect to their sum.		✓	✓
EM 2nd layer	R_η	Defined by ratio in η : $E_{3 \times 7}^{S_2}/E_{7 \times 7}^{S_2}$, for cell energies between 3x7 and 7x7 cells	✓	✓	✓
	w_{η_2}	Lateral shower width defined in 3x5 region of cells in 2nd sampling layers	✓	✓	✓
	R_ϕ	Defined by ratio in ϕ : $E_{3 \times 3}^{S_2}/E_{3 \times 7}^{S_2}$ between cell energies in 3x3 with respect to 3x7 cells			✓
Hadronic leakage	R_{had_1}	Ratio E_T^{had}/E_T in the first hadronic sampling, used when $ \eta < 0.8$ or $ \eta > 1.37$	✓	✓	✓
	R_{had}	Ratio E_T^{had}/E_T over all hadronic calorimeter samplings, used when $0.8 < \eta < 1.37$	✓	✓	✓

Table 5.1: Shower shape variables used to define the photon identification criteria [98]. E_i denotes the energy in the i -th calorimeter cell. E^{S_N} denotes the energy collected in the N -th longitudinal layer of the EM calorimeter.

The loose and medium criteria are predominantly used to trigger photon and diphoton events, and are defined consistently between converted and unconverted photon events since the trigger cannot distinguish between these. The loose criterion was applied to the 2015 and 2016 data to select photon and diphoton events; from 2017 onwards the medium criterion was used to maintain

an acceptable trigger rate. The tight criterion is a subset of those events passing medium achieved by applying an additional set of criteria, and is the dominant identification criterion applied now to Run 2 analyses, including the one presented in Chapter 6 of this thesis. The different geometric regions of the ATLAS calorimeters affect the resulting shower shape, so as a consequence the precise cut values used to define the identification criteria are optimised separately in bins of $|\eta|$, as well as E_T , for all three identification criteria. The selection values used to define the tight criterion are optimised using a multivariate machine learning technique, where sets of MC simulated events are used to define the signal and background contributions and to train the multivariate classifier. For the signal photons, $Z \rightarrow \ell\ell\gamma$ events are used for photons with $E_T < 25$ GeV, and events with $E_T > 25$ GeV are defined using inclusive-photon production. This process is undertaken separately for converted and unconverted photons.

The tight photon identification efficiency is shown in Figure 5.13a for unconverted photons, and Figure 5.13b for converted photons, where each figure also includes a comparison between the selections defined in separate E_T bins (labelled E_T -dependent), versus those defined independently of the E_T value (E_T -independent). For photons with $E_T > 40$ GeV, the tight identification efficien-

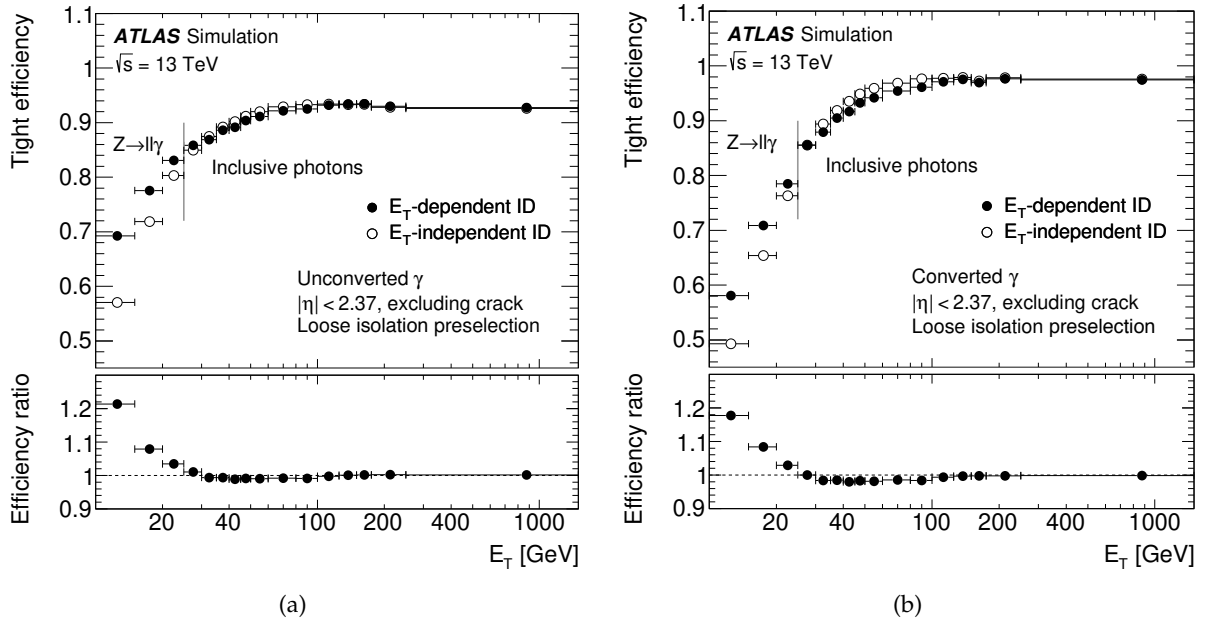


Figure 5.13: Tight photon identification efficiency distributions, as a function of the photon energy E_T , for 5.13a unconverted and 5.13b converted signal photons [90]. Each distribution compares E_T -dependent and E_T -independent identification selections. The distribution in the bottom panel of each figure is defined by taking the ratio between the E_T -dependent and -independent efficiencies.

cy is $\sim 85\%$ which increases to $\geq 92\%$ for $E_T > 100$ GeV, while the background rejection is factor is around 5000. Comparatively, the loose identification efficiency is around 99% for photons with $E_T > 40$ GeV, however the background rejection factor is only around 1000. The tight identification efficiency drops as a function of pile-up, about 10% as $\langle\mu\rangle$ increases from 10 to 70.

5.4.2 Photon isolation

To further suppress the hadronic jet background events, photon candidates must be *isolated* from other nearby charged particle tracks in the ID, or the amount of energy deposited in the calorimeters. The isolation criteria are therefore defined in two classes, the *track isolation* and the *calorimeter isolation*.

The raw calorimeter isolation variable, E_T^{iso} is defined by summing the transverse energies of clusters whose barycentre is located within a cone centred around the photon cluster's barycentre [94]. Taking this raw isolation variable, a few parameters are subtracted to produce the corrected calorimeter isolation variable, E_T^{cone} . Firstly the energy of the photon itself is removed from E_T^{iso} by subtracting the energy contained in a $\Delta\eta \times \Delta\phi = 5 \times 7$ region of cells (middle layers of the EM calorimeter) around the EM cluster's barycentre. A leakage correction is also subtracted, $E_{T, \text{leakage}}$, parameterised as a function of η and E_T , which is defined using a set of single electron or photon MC samples. Finally a pile-up correction factor, $E_{T, \text{pile-up}}$, is subtracted which varies as a function of η [99]. After this, the fully corrected isolation variable is obtained, where two cone sizes, $\Delta R = 0.2$ and 0.4 , are used to define the photon isolation selection criteria.

The track isolation variable, p_T^{cone} , is calculated by defining a cone within $\Delta R = 0.2$ centred around the photon cluster direction, and then summing the transverse momentum of those tracks which fall within the cone. Of these identified tracks, those matched to a converted photon or an electron are excluded. Additionally, the tracks must also satisfy the following criteria to be included in the sum:

- $p_T > 1$ GeV and $|\eta| < 2.5$;
- at least seven silicon hits (in total as measured by the Pixel and SCT detectors);
- at most one hit is allowed to be shared between the Pixel and SCT detectors;
- at most two missing hits in the Pixel and SCT detectors;
- at most one missing hit in the Pixel detector;

There are three photon isolation working points defined in terms of the selections applied on E_T^{cone} for the calorimeter isolation, and p_T^{cone} for the track isolation. These are summarised in Table 5.2. The efficiency of each photon isolation working point is determined using MC simulated events

Working point	Calorimeter isolation	Track isolation
Loose	$E_T^{\text{cone}, \Delta R=0.2} < 0.065 \times E_T$	$p_T^{\text{cone}, \Delta R=0.2} / E_T < 0.05$
Tight	$E_T^{\text{cone}, \Delta R=0.4} < 0.022 \times E_T + 2.45 \text{ GeV}$	$p_T^{\text{cone}, \Delta R=0.2} < 0.05$
TightCaloOnly	$E_T^{\text{cone}, \Delta R=0.4} < 0.022 \times E_T + 2.45 \text{ GeV}$	-

Table 5.2: Selection criteria used to define the photon isolation working points [90].

of radiative Z boson decays and inclusive-photon production similar to those used to determine the photon identification efficiency. The ratio between data and the MC events is computed, and the uncertainty is taken as a source of systematic uncertainty associated with the photon isolation selections. This is calculated individually for each data-taking year, photon conversion type, and for each isolation working point. The isolation efficiencies as a function of E_T are displayed in Figure 5.14 for unconverted and converted photons. These efficiencies also vary slightly (up to $\sim 10\%$) as a function of $|\eta|$ due to the geometry of the ATLAS calorimeters. The loose working point has an efficiency of around 60% for low- E_T photons, which increases up to 90-100% for $E_T \gtrsim 40 - 50$ GeV.

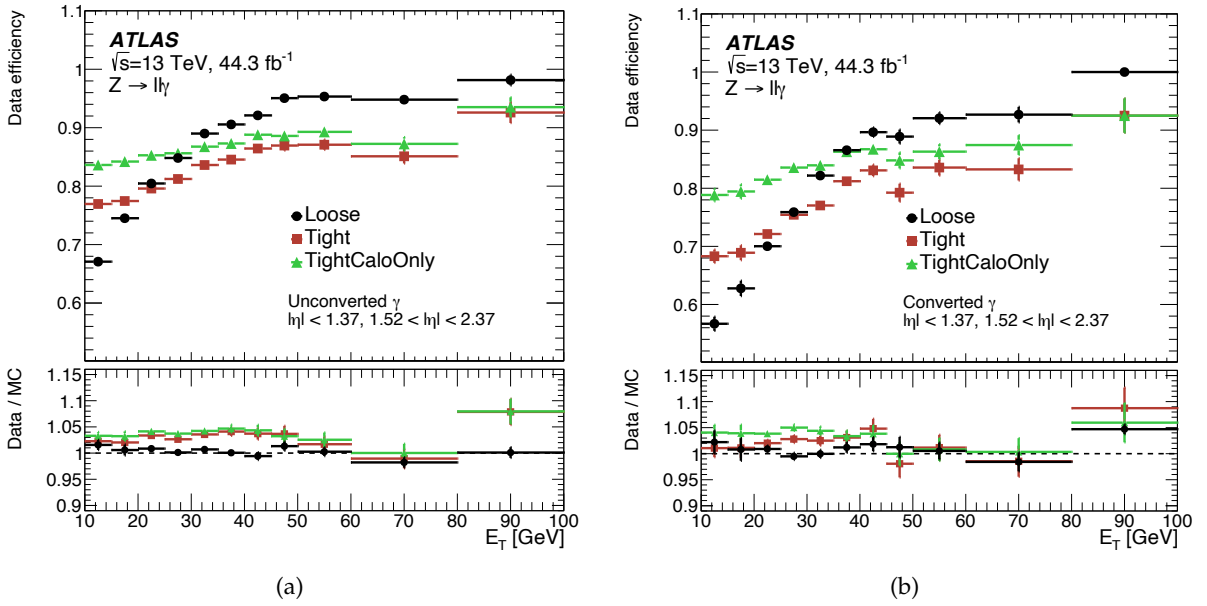


Figure 5.14: Photon isolation efficiency distributions evaluated using $Z \rightarrow \ell\ell\gamma$ events, as a function of photon E_T [90]. Each of the three isolation working points, as defined in Table 5.2 are shown. The distribution in the bottom panel of each figure is defined by taking the ratio between data and MC simulated events.

The photon identification and isolation selections constitute part of the event selection used to select photons suitable for physics analysis. Further analysis level selections, specific to the analysis presented in this thesis, will be discussed in section 6.3.

5.5 Electron performance

This section will outline the additional selection criteria which is applied after reconstruction of the electron candidates. Certain quality criteria are defined to improve the selection of prompt electrons and to minimise electrons originating from hadronic jets, considered as background events. As introduced in section 5.4 for photons, this section presents the electron identification and isolation criteria, which largely follows the same procedure as defined for photons.

An identification algorithm is used to probabilistically determine whether an electron candidate derives from signal or background events. In addition to the variables used for photons (defined in Table 5.1), there are a few additional variables defined for electrons which make use of measurements obtained in the inner detector, the calorimeter, and a combination of both. These include properties of the primary electron track such as number of hits in various layers of the ID (n_{IBL} , n_{Pixel} , n_{Si}), transition radiation measured in the TRT, and the geometric compatibility between the electron track and the reconstructed cluster [94]. Similarly to photons, there are three electron identification criteria defined (*loose*, *medium* and *tight*) which are individually optimised using simulated events for 9 $|\eta|$ ranges, and 12 E_T ranges. The identification efficiencies for each of the three identification working points (*loose*, *medium* and *tight*) are on average 93%, 88% and 80% respectively for electrons produced in usual electroweak processes; these increase slightly as E_T increases.

In addition to the identification requirements, it's also possible to further discriminate between signal and background electron candidates by, like for photons, defining electron isolation criteria. Electrons use the same calorimeter isolation observable, E_T^{iso} , as was defined for photon isolation in section 5.4.2, though only a cone size of $\Delta R = 0.2$ is used. The track isolation parameter is defined differently for electrons, p_T^{varcone} : a variable cone size is defined which decreases in size as the electron transverse momentum increases. The size of the cone, ΔR , is computed to be:

$$\Delta R = \min \left(\frac{10}{p_T[\text{GeV}]} , \Delta R_{\text{max}} \right), \quad (5.3)$$

where $\Delta R_{\text{max}} = 0.2$ is the maximum considered cone size. The considered tracks are also required to either be loosely associated to the primary vertex, or to satisfy the requirement $|\Delta z_0| \sin \theta < 3$ mm where the longitudinal impact parameter, $|\Delta z_0|$, is defined in relation to the selected primary vertex. The electron isolation criteria are defined via two different approaches, either by targeting a certain isolation efficiency (defined as the *gradient* working point), or by defining fixed values of the selection variables (the *highPtCaloOnly*, *loose*, and *tight* working points). The selection criteria applied when using the gradient working point vary so to provide a 90% efficiency when $p_T = 25$ GeV, and 99% when $p_T = 60$ GeV, independent of $|\eta|$. The electron isolation working point definitions are presented in Table 5.3.

Ultimately, the specific electron isolation working point chosen depends on the individual physics analysis since there is a trade-off between identifying prompt, isolated electrons with high efficiency, and aggressively rejecting what is considered background electrons originating from hadron decays or light hadrons that have been mislabelled as electrons. Given the analysis presented in this thesis contains only photons in the final state, none of the electron isolation working points are applied as part of the selection criteria.

Working point	Calorimeter isolation	Track isolation
Gradient	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with $E_T^{\text{cone}, \Delta R=0.2}$)	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with $p_T^{\text{varcone}, \Delta R=0.2}$)
HighPtCaloOnly	$E_T^{\text{cone}} < \max(0.015 \times p_T, 3.5 \text{ GeV})$	-
Loose	$E_T^{\text{cone}} / p_T < 0.20$	$p_T^{\text{varcone}, \Delta R=0.2} < 0.15$
Tight	$E_T^{\text{cone}} / p_T < 0.06$	$p_T^{\text{varcone}, \Delta R=0.2} < 0.06$

Table 5.3: Definition of the working points used for electron isolation [90]. All working points use a cone of size $\Delta R = 0.2$ to define the calorimeter isolation.

5.6 Conclusion

The various sub-detectors and specifically chosen detector technologies used in the ATLAS detector allow for a wide variety of particles to be measured and thus used for physics analysis. The identification, reconstruction and energy calibration of electrons, and in particular photons is especially important for the $H \rightarrow \gamma\gamma$ analysis which will be presented in Chapter 6. Precision measurements of Higgs boson physics in the $\gamma\gamma$ channel, such as cross-section measurements [48] and most recently the measurement of the Higgs boson mass with the Run 2 dataset [100], are overwhelmingly dominated by systematic uncertainties deriving from the e/γ energy calibration. The specific photon identification and isolation working points used in the analysis will be detailed as part of the event selection criteria detailed in section 6.3.

6 | Determining the Higgs boson width in the diphoton decay channel

This chapter presents the determination of the Higgs boson width, Γ_H , in the $H \rightarrow \gamma\gamma$ channel using the Run 2 dataset, which corresponds to 140.1 fb^{-1} collected at $\sqrt{s} = 13 \text{ TeV}$. This analysis exploits the interference effects due to the presence of the resonant signal and continuum QCD background with the same diphoton final state. The model-independent nature of this measurement technique is beneficial given the fact that the Higgs width property is so inextricably linked with the possible Higgs boson decay modes through equation 2.32, thus making it the prime parameter for probing the existence of BSM physics.

This chapter will begin with a general overview of the $H \rightarrow \gamma\gamma$ analysis strategy in section 6.1, where an outline of the various analysis ingredients required to measure the Higgs boson width in the $H \rightarrow \gamma\gamma$ channel will be presented. During this overview, each remaining section of this chapter will be subsequently introduced.

6.1 General $H \rightarrow \gamma\gamma$ analysis strategy

The $H \rightarrow \gamma\gamma$ decay mode is one of the best channels to measure properties of the Higgs boson, as mentioned in section 2.2.5, due to the very clean experimental signature of the two photons in the ATLAS detector, the excellent photon reconstruction, and well understood background processes. Furthermore, the non-negligible effects on the diphoton invariant mass distribution due to interference between the resonant signal and background processes, and the resulting dependence of these effects on the Higgs boson width as presented in Chapter 3, make it the ideal channel for measuring the Higgs boson width.

The diphoton invariant mass, $m_{\gamma\gamma}$, is the main experimental observable, where the Higgs boson signal manifests itself as an excess of events - a narrow *peak* - over a monotonically-decreasing background due to the SM $\gamma\gamma$, γ +jet, and di-jet background processes. The central value of the peak (the peak position) corresponds to the mass of the Higgs boson, m_H . As detailed in section 3.3, the presence of interference effects causes a distortion in the shape of the $m_{\gamma\gamma}$ distribution,

notably including a shift in the peak position towards lower values of $m_{\gamma\gamma}$. These effects are proportional to the Higgs boson total width, Γ_H . The analysis presented in this chapter performs a binned maximum likelihood shape fit over the full $m_{\gamma\gamma}$ distribution, to extract the value of Γ_H . Fitting the full lineshape in this way allows for both shape changes in the peak position as well as yield effects due to the interference contributions, to be captured. The procedure is thus a more sophisticated version of simply measuring the mass shift of the peak position due to the effects of only the real component of the interference, since it captures information across the entire $m_{\gamma\gamma}$ distribution. Throughout this analysis it is useful to define the width parameter of interest (POI), λ , as the Higgs boson width normalised by the theoretically predicted SM value (equation 2.2.2) at $m_H = 125$ GeV as:

$$\lambda = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\Gamma_H}{4.09 \text{ MeV}}. \quad (6.1)$$

Events are initially required to contain two isolated photons, that derive from the same production vertex, and are well reconstructed with an invariant mass of the diphoton system to be between 105 GeV and 160 GeV. Since the Higgs boson mass is known to be ~ 125 GeV and the width of the reconstructed signal peak is $\sim 1 - 3$ GeV, the signal region is defined by the window $m_{\gamma\gamma} \in [120 \text{ GeV}, 130 \text{ GeV}]$. The regions $m_{\gamma\gamma} \in [105 \text{ GeV}, 120 \text{ GeV}]$ and $m_{\gamma\gamma} \in [130 \text{ GeV}, 160 \text{ GeV}]$, are what's known as data *sideband* regions which are used to model the background components, and extrapolate to the signal region. Details pertaining to the dataset and MC simulated samples are described in section 6.2. The event selection performed to obtain the two final state photons, and discriminate these from background processes, is described in section 6.3.

Events are divided into orthogonal *event categories*, defined by certain kinematic selection criteria that are optimised in order to maximise sensitivity to the aforementioned interference effects and hence the sensitivity to the Higgs boson width by construction. Section 6.4 presents the studies conducted to define the event categories used for this analysis.

In each event category, the shape of the signal, interference and background processes as a function of $m_{\gamma\gamma}$ are modelled with analytical functions, as will be shown in detail in sections 6.5 - 6.7. The expected number of events in each category deriving from each of these processes are also detailed in the respective sections. The analytical functions are combined into a total signal-plus-interference-plus-background model by summing together the individual components, which is then used to perform the maximum likelihood fit over $m_{\gamma\gamma}$ simultaneously in all event categories to extract Γ_H . This total model can be generally defined as

$$f_{\text{total}} = \mu N_S f_S + \sqrt{\mu\lambda} N_{I(gg)} f_{I(gg)} + \sqrt{\mu\lambda} N_{I(qg)} f_{I(qg)} + N_B f_B, \quad (6.2)$$

where N_X corresponds to the yield of each process X , f_X denotes the analytical function used to model each process X , μ is the signal strength which parametrises the agreement between the SM predicted cross-section and the measured value, and $\lambda = \Gamma_H / \Gamma_H^{\text{SM}}$ is the Higgs boson width

parameter of interest.

Experimental and theoretical systematic uncertainties which can alter the nominal $m_{\gamma\gamma}$ distribution are included in this model as a set of nuisance parameters. These uncertainties will be discussed in section 6.8. The definition of the total likelihood function is presented in section 6.9, which is then used to perform the fit to obtain the results of the Higgs boson width in section 6.10. Section 6.11 extrapolates the Run 2 sensitivity of the analysis to the expected sensitivity following the collection of the dataset expected by the end of the HL-LHC data-taking period. This section includes a description of the extrapolation procedure as well as possible future analysis improvements that could be made to further enhance the experimental sensitivity. Concluding remarks about the results and its implications within the current landscape of Higgs boson property measurements will be discussed in section 6.12.

6.2 Data and MC simulated samples

This section provides explicit details on the data and MC simulated events, in sections 6.2.1 and 6.2.2 respectively, which are used to perform the presented analysis.

6.2.1 Data samples

The analysis presented in this chapter uses pp collision data collected by the ATLAS detector at $\sqrt{s} = 13$ TeV between the years 2015 and 2018, amounting to a total integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1}$ [101]. This recorded data has been subject to data quality checks before being deemed suitable for physics analyses; more details will be discussed in section 6.3. During this data-taking period, the mean number of inelastic interactions occurring per bunch crossing was $\langle\mu\rangle = 34$, as can be seen in Figure 4.4b. A breakdown of the luminosity and $\langle\mu\rangle$ per year is presented in Table 6.1. The expected number of Higgs bosons produced is also reported, making use of equation 4.1. The last column lists the total number of expected $H \rightarrow \gamma\gamma$ events per year, obtained by multiplying the total expected number of Higgs bosons by the branching ratio for the diphoton decay channel, $\text{BR}(H \rightarrow \gamma\gamma) = 0.0023$.

Before ATLAS data is used to obtain the final analysis results, it is common practice to define a fake dataset which can be used in place of the real data to, for example, define the optimal event categorisation (based on the resulting sensitivity to the POI) and to obtain the *expected* results. This is achieved by generating an *Asimov dataset* [102] which is constructed as a binned dataset whereby the contents of each bin is determined by calculating the expected yield for a specific set of model parameter values. The parameter values are set to their expected values, which can be either the theoretically predicted values (from the SM), or the latest experimentally measured values (for example in the case of the Higgs boson mass). When an Asimov dataset is used to

Year	Luminosity [fb^{-1}]	$\langle\mu\rangle$	$N_H^{\text{exp.}}$	$N_{H\rightarrow\gamma\gamma}^{\text{exp.}}$
2015	3.24 ± 0.04	13	1.8×10^5	4.1×10^2
2016	33.40 ± 0.30	25	1.8×10^6	4.2×10^3
2017	44.63 ± 0.50	38	2.5×10^6	5.7×10^3
2018	58.79 ± 0.64	36	3.3×10^6	7.5×10^3
Total	140.07 ± 1.17	34	7.8×10^6	1.8×10^4

Table 6.1: Total integrated luminosity collected by the ATLAS experiment during the 2015-2018 data-taking period, and the average number of interactions per bunch crossing [101]. The expected total number of Higgs bosons that are produced, and the number of expected Higgs bosons decaying into two photons, are also listed.

maximise the likelihood function, it is expected that the best-fit parameter values equates to those values used to generate the dataset.

6.2.2 MC samples

Samples of simulated Monte Carlo (MC) events are used at various stages in the analysis workflow, in particular to identify the appropriate choice of analytical functions to model the diphoton distributions for the signal, interference and background components, as well as the experimental shape systematic uncertainties associated to the photon energy scale and resolution. This section presents details of all MC samples used in this analysis.

Generation of the signal and interference processes:

Prior to the commencement of this analysis, there was no MC event generator publically available that could generate either of the gg - or qg - initiated diphoton interference processes. We were aware of private studies and code development of the SHERPA event generator [103] for these interference components, and so conversations with the authors of the SHERPA generator ensued to discuss the feasibility of obtaining a public SHERPA release which included such processes. A novel *Higgs interference module* was released in SHERPA version number 2.2.11, which can generate interference events for the diphoton final state. This module allows the user to specify which processes are to be included in the matrix element calculation, using two input parameters: `HIGGS_INTERFERENCE_MODE` and `HIGGS_INTERFERENCE_ONLY`. The `HIGGS_INTERFERENCE_MODE` parameter selects which of the signal or background diagrams are to be included (and if tree or loop diagrams are allowed), while the `HIGGS_INTERFERENCE_ONLY` parameter selects whether to include interference processes. Since SHERPA is the only event generator able to generate interference events, this was the reason it was chosen. More details on the SHERPA generation syntax can be found in the SHERPA manual [103]. Extensive studies and discussions on the custom sample generation procedure followed, and was subsequently approved by the ATLAS Physics Modelling Group allowing this procedure to be used for official ATLAS MC sample production.

For the generation of both signal and interference samples, the Higgs interference module in SHERPA version 2.2.11 has been used to generate the contributions independently. Since the background process is also generated with SHERPA, and the interference occurs between the signal and background processes, we also use SHERPA to produce the resonant signal MC so to be consistent. All events are generated with a Higgs boson mass set to $m_H = 125$ GeV, according to the latest and most precise ATLAS Higgs mass measurement value, from the Run 1 and Run 2 $H \rightarrow ZZ^*$ measurement combination [22].

The matrix element calculation is performed at NLO in QCD for the signal and gg -interference process, and LO for the qg -interference process. The parton shower is based on the Catani-Seymour dipole factorisation [104], which is the default parton shower in SHERPA. The samples are generated using the NNPDF30_nnlo_as_0118_hessian PDF set [105]. Each generated sample is normalised by the cross-section values calculated in SHERPA for the SM width sample, given the measured on-shell signal strengths of Higgs boson production across different decay channels are thus far all compatible with SM expectations [2].

Events are generated separately for each desired process, be it the signal, interference or background contribution. To generate the resonant signal $gg \rightarrow H \rightarrow \gamma\gamma$ process with SM width ($\Gamma_H = \Gamma_H^{\text{SM}}$, so $\lambda = 1$) which corresponds to the $|S|^2$ term in equation 3.14, the following options are used in the generator:

$$\text{HIGGS_INTERFERENCE_MODE} = 1 \quad (6.3)$$

$$\text{HIGGS_INTERFERENCE_ONLY} = 0. \quad (6.4)$$

The generation of only gg -interference events, which corresponds to the last two terms in equation 3.14, is performed with the following settings:

$$\text{HIGGS_INTERFERENCE_MODE} = 3 \quad (6.5)$$

$$\text{HIGGS_INTERFERENCE_ONLY} = 1; \quad (6.6)$$

for only qg -interference events instead the following options are required:

$$\text{HIGGS_INTERFERENCE_MODE} = 5 \quad (6.7)$$

$$\text{HIGGS_INTERFERENCE_ONLY} = 1. \quad (6.8)$$

Events corresponding to the signal and two interference processes are first simulated with SHERPA, using the options listed above, and are then passed through a full ATLAS detector simulation [106] using the GEANT4 software program [107] to simulate the detector response to the given physics event. The $m_{\gamma\gamma}$ invariant mass distributions obtained for the gg - and qg -interference processes at *generator level*, is shown in Figure 6.1a. The *reconstruction level* distribution, meaning

after the events have been passed through the detector simulation, is shown in Figure 6.1b. The broadening of the peaks is due to the *smearing* effect caused by the detector response. As expected from the theoretical calculations (section 3.3), the shape of the sub-dominant qg -interference has an opposite global sign with respect to the gg -interference. Combining these contributions results in a lesser net effect than only considering the leading gg -interference contribution.

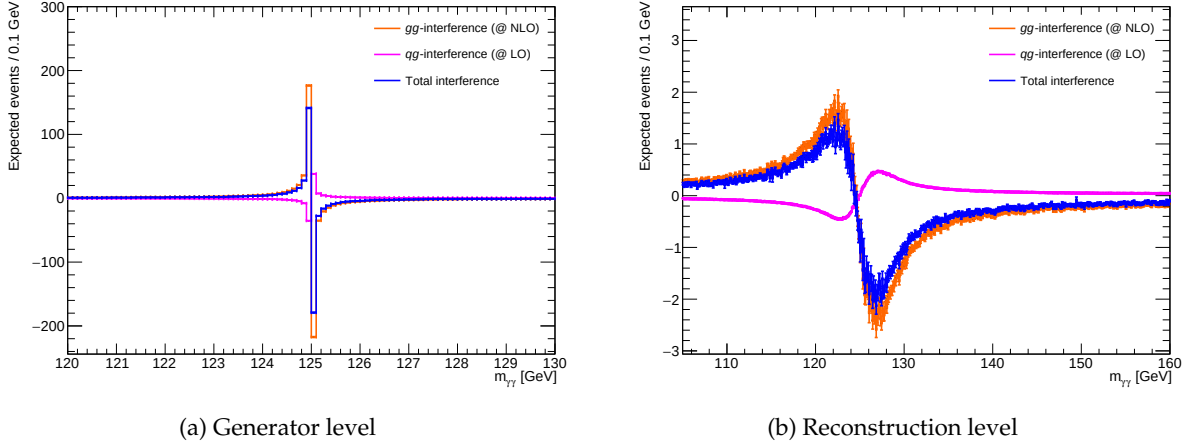


Figure 6.1: Simulated diphoton invariant mass distributions for the interference processes scaled to 140 fb^{-1} .

This new official interference MC generation is important not only for the Higgs boson width analysis, but it also affects any precision $H \rightarrow \gamma\gamma$ measurement. The total uncertainty on the Higgs boson mass measurement in the $H \rightarrow \gamma\gamma$ channel, now less than 150 MeV, is reaching a level where interference effects are no longer small when compared to other systematic uncertainties, and a proper treatment of such effects on the signal peak position is required. A comparison between the inclusive $m_{\gamma\gamma}$ distribution with and without interference effects is shown in Figure 6.2, where the shift in the mean peak position, calculated to be 78 MeV, is clearly visible. Discussions are on-going on how to exactly treat these interference effects in the $H \rightarrow \gamma\gamma$ Higgs boson mass measurement, which is the most precise determination of m_H to date; further details can be found in [100].

For the purpose of signal and interference modelling, one additional sample with an alternate Higgs boson width value, $\lambda = 100$, has been produced for each process. This sample has also been passed through the full ATLAS detector simulation, such that the signal and interference modelling approaches (which will be discussed in sections 6.5 and 6.6 respectively) can be validated. The only alteration made to the generation setup to produce these samples is to multiple the originally set Higgs width, Γ_H^{SM} , by a factor 100.

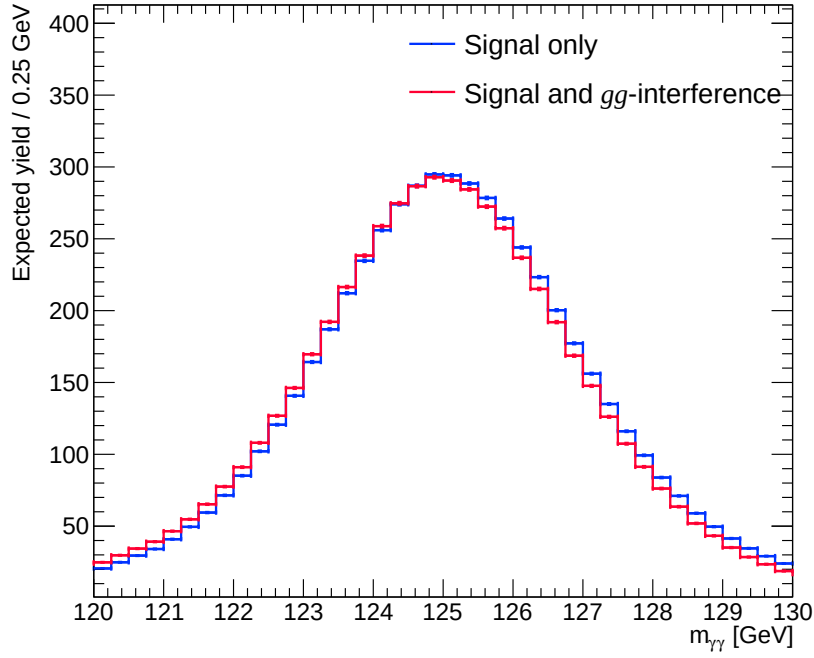


Figure 6.2: Distribution of the $m_{\gamma\gamma}$ invariant mass comparing the resonant signal peak when considering the signal only process S in red, with the inclusion of interference contributions $S + I(gg)$, in blue. The relative shift in the peak position is -78 MeV.

Corrections to the simulated events:

The signal cross-section from Sherpa is calculated at NLO in QCD, however the highest accuracy with which this cross-section has been calculated is N³LO in QCD [108]:

$$\sigma_{gg \rightarrow H \rightarrow \gamma\gamma}^{\text{N}^3\text{LO}} = 48.52 \text{ pb}_{-3.27}^{+2.22} (\text{theory}) \pm 1.56 \text{ pb} (\text{PDF} + \alpha_S). \quad (6.9)$$

As such, a correction factor, K_S , is applied to the signal yield which is computed by taking the relative difference between the cross-section at N³LO and that from Sherpa at NLO, i.e. $(48.52 \text{ pb} \times 2.27 \cdot 10^{-3}) / 0.079 \text{ pb} = 1.4$. The interference yields are also scaled by $\sqrt{K_S}$.

The highest order gg -interference cross-section calculation has been performed at NNLOsv as introduced in section 3.3.3. The cross-section computations presented in [41] correspond to those calculated at $\sqrt{s} = 13.6$ TeV. Through private communication with the authors of this paper (specifically Fabrizio Caola and Federica Devoto), the cross-sections were also calculated at $\sqrt{s} = 13$ TeV, so that they could be used to correctly scale the interference yields in this analysis. The gg -interference cross-sections computed at NLO and NNLOsv, at $\sqrt{s} = 13$ TeV, are:

$$\sigma_{gg \rightarrow (H \rightarrow) \gamma\gamma}^{\text{NLO}} = -0.71 \text{ fb}_{-0.16}^{+0.20}, \quad (6.10)$$

$$\sigma_{gg \rightarrow (H \rightarrow) \gamma\gamma}^{\text{NNLOsv}} = -1.16 \text{ fb}_{-0.13}^{+0.08}. \quad (6.11)$$

A gg -interference scale factor, K_I , defined by taking the ratio between the cross-section computed at NLO and that at NNLOsv i.e. $-1.16 \text{ fb} / -0.71 \text{ fb} \sim 1.65$, is applied to the gg -interference yield. Note these cross-sections were computed in a different phase space compared to the Sherpa generation, hence the scale factor is defined by taking the ratio between the values presented in equations 6.10 and 6.11, rather than using the cross-section obtained via Sherpa.

Simulation of SM background events:

The irreducible QCD $\gamma\gamma$ background events are simulated using SHERPA, where $\gamma\gamma+0,1$ jet events are generated at NLO while $\gamma\gamma+2,3$ jet are at LO. The parton shower is used with the default SHERPA settings, and the PDF set is CT10. The generation is done with a phase space restriction of $m_{\gamma\gamma} \in [90 \text{ GeV}, 175 \text{ GeV}]$ to maximise the number of events produced in the region of interest around the Higgs boson mass. Once generated, the $\gamma\gamma$ background sample is passed through the ATLAS detector simulation, using a fast simulation [109] approach, known as ‘G4FastCalo’, which approximates the calorimeter response so to reduce the required computing time. This is due to the large numbers of events generated, around 700 million, which are required to be able to model the background with sufficient accuracy.

Table 6.2 summarises details of all the MC simulated samples used in this analysis, and generated at reconstruction level using the full ATLAS detector simulation.

Process	Generator	PDF set	Showering	Γ_H	σ [pb]	Events
ggH	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	Γ_H^{SM}	0.0786	4.99M
ggH	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	$100 \times \Gamma_H^{\text{SM}}$	$7.92 \cdot 10^{-4}$	4.99M
gg-interference	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	Γ_H^{SM}	$-9.37 \cdot 10^{-4}$	33.45M
gg-interference	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	$100 \times \Gamma_H^{\text{SM}}$	$-1.00 \cdot 10^{-3}$	19.57M
qg-interference	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	Γ_H^{SM}	$8.27 \cdot 10^{-5}$	34.74M
qg-interference	SHERPA	NNPDF30_nnlo_as_0118_hessian	SHERPA - CSS	$100 \times \Gamma_H^{\text{SM}}$	$8.37 \cdot 10^{-5}$	19.96M
$\gamma\gamma$	SHERPA	CT10	SHERPA - CSS	Γ_H^{SM}	51.8	720M

Table 6.2: Summary of the MC simulated samples which have been passed through the ATLAS detector simulation. All samples listed are passed through the full detector response simulation in GEANT4, with the exception of the $\gamma\gamma$ background sample which uses the ‘G4FastCalo’ fast simulation instead. ‘M’ denotes millions of events.

Since this analysis aims to measure the Higgs boson width, it is imperative to understand how the signal and interference $m_{\gamma\gamma}$ distributions vary as a function of Γ_H . Ideally we want a continuous description of $m_{\gamma\gamma}$ as a function of Γ_H however since it is not possible to generate infinitely many individual samples with different Higgs width values, an alternate solution must be found to somehow interpolate between the samples we do generate. This is achieved using a *reweighting* procedure, which will be outlined in section 6.2.3. Prior to this however, the samples we want to interpolate between must be generated; this will be discussed below.

Generation issues with large sample sizes:

In this analysis there are some complications in the generation procedure. The first one being that when you generate a MC sample you want the number of events generated to be large enough so that each distribution is sufficiently populated, and hence the statistical uncertainty per bin is small (meaning less than $\mathcal{O}(10\%)$). In general, the SHERPA event generator generates weighted events whose value, w , can be negative. In the case of both required interference processes, these weights often have absolute value very close to zero. The consequence of so many negatively weighted events, is essentially that they cancel out events with positive weights. The statistical error, $\delta\sigma$, on the generated cross-section goes like:

$$\frac{\delta\sigma_I}{\sigma_I} = \frac{\sum w^2}{|\sum w|}, \quad (6.12)$$

where here σ_I denotes the cross-section value for either interference process. Although $\delta\sigma_I$ is finite, a large number of events, more than $\mathcal{O}(10\text{M})$ must be generated for the uncertainty to be small enough ($\mathcal{O}(10\%)$) and therefore the modelling sufficiently accurate. This effect can be seen in Figure 6.1b, where despite around 35 million events being generated and the relatively coarse 100 MeV binning, the statistical uncertainty in each bin within the signal region $m_{\gamma\gamma} \in [120 \text{ GeV}, 130 \text{ GeV}]$ is still quite large, $\mathcal{O}(5\text{-}30\%)$. To correctly simulate events as measured by the ATLAS detector, all of the generated samples should be passed through a simulation of the expected ATLAS detector response. The generation at reconstruction level simulating the full ATLAS detector response is unfeasible for a large number of individual samples, given how many events (therefore computing time) are required for the interference processes to obtain a reasonable statistical error. One solution to reduce the computation time is to use the fast ATLAS detector simulation, as is used for the $\gamma\gamma$ background sample. This is a factor 33 times faster to process than using the full GEANT4 simulation. We investigated the impact on the $m_{\gamma\gamma}$ resolution to ascertain if there is any significant alteration of the $m_{\gamma\gamma}$ distribution that would deteriorate the sensitivity to the effects we aim to study. When comparing the $m_{\gamma\gamma}$ distributions the G4FastCalo simulation reveals a roughly 20% relative difference in resolution compared to the distribution obtained when using the full GEANT4 detector simulation. Since the nature of this analysis relies on the measurement of small deviations in the mean and width of the $m_{\gamma\gamma}$ distribution, this 20% difference was too large, and hence the G4FastCalo simulation is clearly not an appropriate choice to produce more alternate width signal and interference samples.

Instead of generating at reconstruction level a series of samples with various Higgs width values, an alternative solution is to generate a set of samples at generator level instead and to use a process known as event *reweighting* to obtain the corresponding samples at reconstruction level. This procedure is described in section 6.2.3.

6.2.3 Simulated events with non-SM Γ_H values

Only signal and interference MC samples produced at reconstruction level using the *full* ATLAS detector simulation are sufficiently accurate to be used in this analysis. Two such high-statistics samples that have been generated, one with the nominal $m_H = 125$ GeV, $\lambda = 1$ parameters set, and one alternate Higgs boson width value of $\lambda = 100$ for each process. We will use a reweighting technique to obtain an additional set of MC samples with intermediate Higgs width values. These samples are vital to model the signal (interference) process at discrete values of λ , and be used as inputs, and to validate, the methods outlined in section 6.5 (section 6.6) to obtain a continuous description of the $m_{\gamma\gamma}$ distribution for the signal (interference) process when varying λ . This is achieved by reweighting the $m_{\gamma\gamma}$ distributions of generator level samples, to reconstruction level.

For each of the signal and two interference processes, generator level samples have been produced with Higgs width values set to $\lambda = 5, 10, 25, 50, 200, 300, 400$. This is possible since generating samples at generator level is sufficiently faster and therefore less computationally intense, than generating samples with the full detector simulation. The following reweighting procedure is then used to obtain the relevant $m_{\gamma\gamma}$ distributions for each of these alternate width samples.

Signal and gg -interference samples: Each MC event can be assigned an *event weight* which enables the user to, for example, enhance a particular region of phase space or to obtain specific kinematic distributions, by enhancing the weights in either that desired part of phase space or the distribution of interest. This is typically calculated by taking ratios of distributions at generator level, and then propagating them to a sample at reconstruction level (commonly known as *reweighting*) so to obtain the desired phase-space enhanced sample, or kinematic distribution. This technique is used in this analysis whereby one-dimensional reweighting using the $m_{\gamma\gamma}$ distribution is employed to obtain signal and gg -interference samples at reconstruction level for samples with various Higgs boson width values. This is achieved by calculating a weight based on the ratio at generator level between the reference sample with width λ , and the desired reconstruction sample with some alternate width λ' . This weight, defined in equation 6.13, is then applied as an event weight to the reference reconstruction level sample, for each process.

$$\begin{aligned} X^{\text{reco.}}|_{\lambda'} &= \left(\frac{m_{\gamma\gamma}^{\lambda'}}{m_{\gamma\gamma}^{\lambda}} \right)^{\text{generator}} \times X^{\text{reco.}}|_{\lambda} \\ &= \text{event weight} \times X^{\text{reco.}}|_{\lambda}, \end{aligned} \quad (6.13)$$

where the distribution given by $X^{\text{reco.}}|_{\lambda'}$ is then at reconstruction level with width $\lambda' \neq \lambda$, for any given kinematic variable, X . Note that since an event weight is applied, it reweights all kinematic distributions, not just $m_{\gamma\gamma}$. For the signal and gg -interference processes, the reference reconstruction level sample is the one generated with $\lambda = 100$. This is because the $m_{\gamma\gamma}$ distribution has a

more broader shape, and so more off-peak events for $\lambda = 100$ compared to the $\lambda = 1$ case. Additionally the analysis sensitivity is expected to be $\mathcal{O}(\lambda = 100)$. To validate that the reweighting procedure correctly models the kinematic distributions at reconstruction level, two closure checks will be performed. The first check applies the event-weight to the reference template at generator level, to confirm the resulting distribution at generator level matches the generated sample at generator level (with the corresponding new width value). This is described by equation 6.14, for some kinematic variable X .

$$X^{\text{generator, rw}}|_{\lambda} = \left(\frac{m_{\gamma\gamma}^{\lambda'}}{m_{\gamma\gamma}^{\lambda}} \right)^{\text{generator}} \times X^{\text{generator}}|_{\lambda'}, \quad (6.14)$$

where the 'rw' index indicates the reweighted distribution. Figures 6.3a and 6.3b display the closure validation plots, specifically the $m_{\gamma\gamma}$ and diphoton transverse momentum, $p_{\gamma\gamma}^T$, for the signal and gg -interference processes respectively. Although statistical fluctuations are evident, especially for the gg -interference process, no significant shape differences are observed between the reweighted distribution, and the distribution generated at reconstruction level. For these closure plots the reference, and subsequently reweighted distribution, have widths corresponding to $\lambda = 50$.

qg -interference samples: For the qg -interference process, given the presence of an additional jet in the event, more information is required to accurately reweight this distribution. In this case, two-dimensional reweighting is done over the $m_{\gamma\gamma}$ and $p_T^{\gamma\gamma}$ variables. This is achieved following a similar procedure to the one mentioned above, but additionally calculating the ratio of $p_T^{\gamma\gamma}$ distributions. In this way a two-dimensional event weight is defined, and applied to reweight the qg -interference reconstruction sample to alternate width samples. In this case, the $\lambda = 1$ reconstruction sample is used as the reference sample. For the qg -interference sample, both the $\lambda = 1$ and $\lambda = 100$ samples were tested to be used as the reference sample at reconstruction level, however it was observed that using the $\lambda = 1$ sample in this case resulted in lower statistical uncertainties in the resulting distribution, as a consequence of the fact that about 40% less events were generated for the $\lambda = 100$ process compared to the $\lambda = 1$ sample (refer to Table 6.2). The same generator level closure check as the signal and gg -interference samples is performed, and the resulting kinematic distributions are shown in Figure 6.4.

In addition to the generator level validation check, a second closure test was undertaken whereby the MC generated sample (specifically the $m_{\gamma\gamma}$ distribution) will be compared at reconstruction level with that obtained via reweighting of a sample with alternate λ value. If the reweighting procedure works, these two distributions should match. For the signal and gg -interference, the closure is performed by reweighting a $\lambda = 100$ sample to $\lambda = 1$, and comparing to a generated $\lambda = 1$ sample. For the qg -interference closure test instead, a $\lambda = 1$ sample was reweighted to $\lambda = 100$ and compared to a generated $\lambda = 100$ sample. Figure 6.5 displays these validation plots,

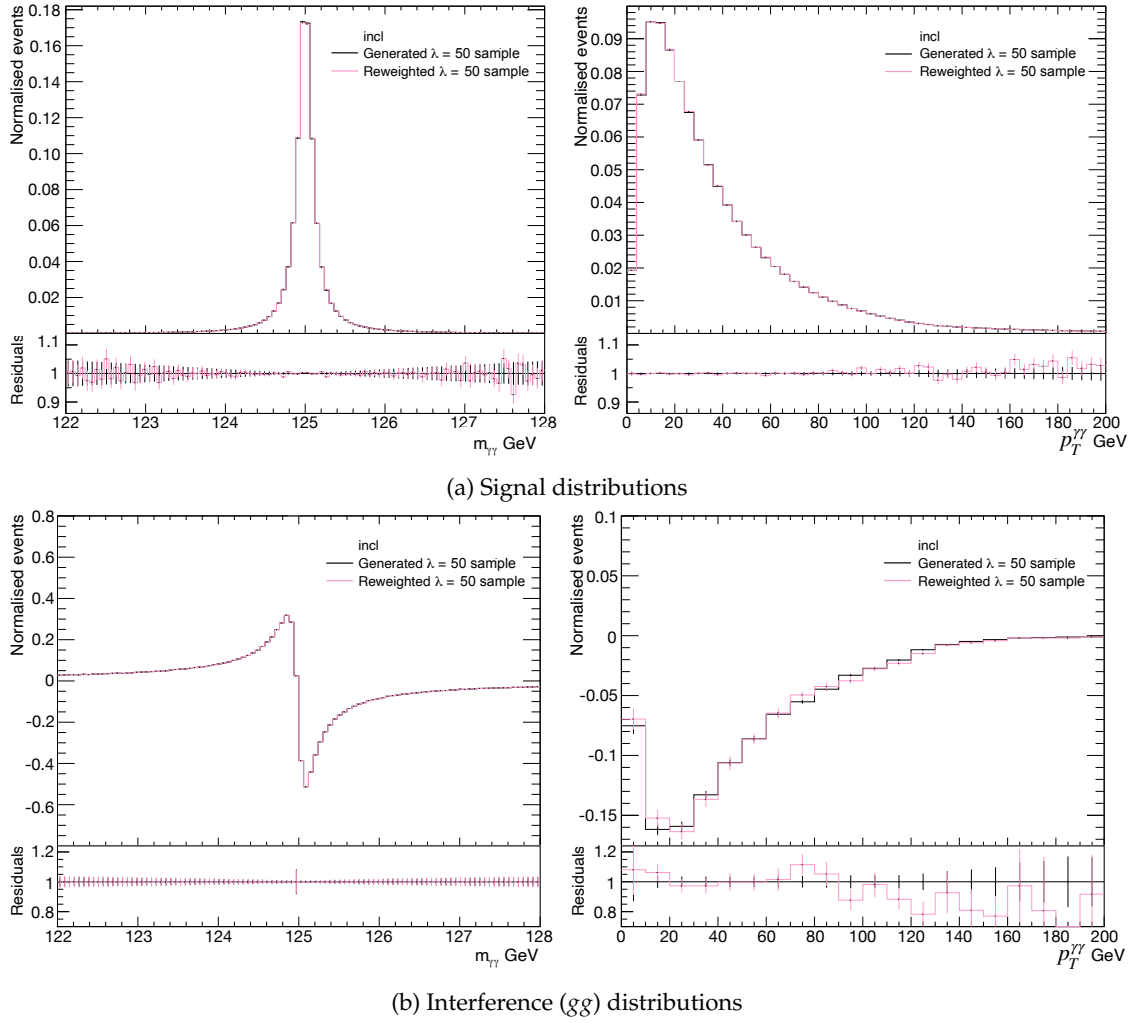


Figure 6.3: Normalised generator level $m_{\gamma\gamma}$ and $p_T^{\gamma\gamma}$ kinematic distributions for $\lambda = 50$, compared to those obtained via the reweighting of a $\lambda = 100$ sample, for the resonant signal (6.3a), and the gg -interference processes (6.3b). The residuals are defined by taking the ratio with respect to the generated sample, per bin. The difference between the generated and reweighted samples is generally less than 10% (with the exception of the $p_T^{\gamma\gamma}$ distribution at very high values where the number of events per bin tends to zero, and so the fluctuations are large).

for each of the signal and interference processes. In all cases, no significant shape differences are observed between the reweighted reconstruction distribution, and the distribution generated at reconstruction level, hence validating the procedure.

6.3 Event selection

Following the reconstruction and identification of photons in an event, as described in chapter 5, further selections are applied on photon kinematic properties in order to suppress the background contributions and maximise the number of signal events. These selections follow the

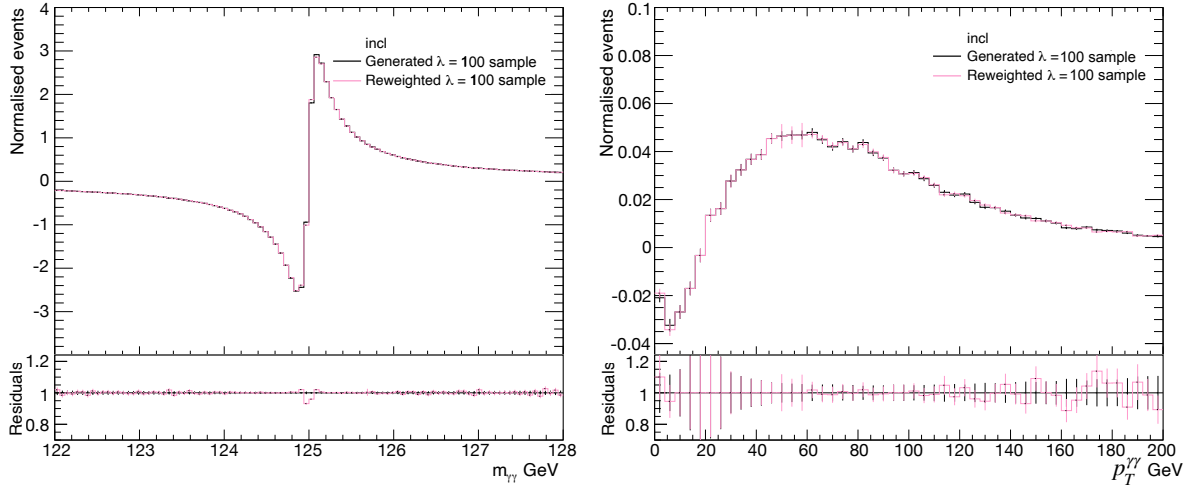


Figure 6.4: Normalised generator level $m_{\gamma\gamma}$ and $p_T^{\gamma\gamma}$ kinematic distributions for $\lambda = 100$, compared with those distributions obtained via the reweighting of a $\lambda = 1$ sample, for the qg -interference process. The residuals are defined by taking the ratio with respect to the generated sample, per bin.

recommendations which have been developed during the early Run 2 analyses and are recommended for use by all analyses conducted within the $H \rightarrow \gamma\gamma$ ATLAS group [110]. An overview of the selection criteria applied to identify $H \rightarrow \gamma\gamma$ events in data will be summarised in this section.

Data is first required to have been collected when all ATLAS sub-detector systems were fully operational, and events have passed the *ATLAS Good Run List* which ensures good data quality. Events are required to contain at least two reconstructed photons, two of which satisfy $p_T > 25$ GeV and $|\eta| < 2.37$, excluding the region $1.37 \leq |\eta| \leq 1.52$ which corresponds to a gap in the detector. The two most energetic (highest p_T) photons in the event are classified as the two final state photon candidates, and are used to define the primary vertex corresponding to the Higgs boson candidate. These photons must have passed the *loose* identification criteria, as defined in chapter 5. All other photons present in the event are discarded.

6.3.1 Diphoton primary vertex

Generally speaking, ATLAS physics analyses define the primary vertex as the one with the largest scalar sum, $\sum p_T^2$, defined by summing the transverse momentum for all tracks associated to that vertex. Since photons do not have an electric charge, they do not leave tracks in the ID and so defining the vertex in this way is sub-optimal for diphoton events. This is especially true for processes with no other particles in the final state, such as $H \rightarrow \gamma\gamma$ events. Instead, a neural-network (NN) algorithm is trained on MC simulated data and used to correctly identify the diphoton primary vertex (PV). This is achieved by assigning a score to all reconstructed vertices in the event, as determined by the NN, which is based on properties of the tracks and candidate primary vertices in the event, and directional information of the photons in the EM calorimeter by exploiting

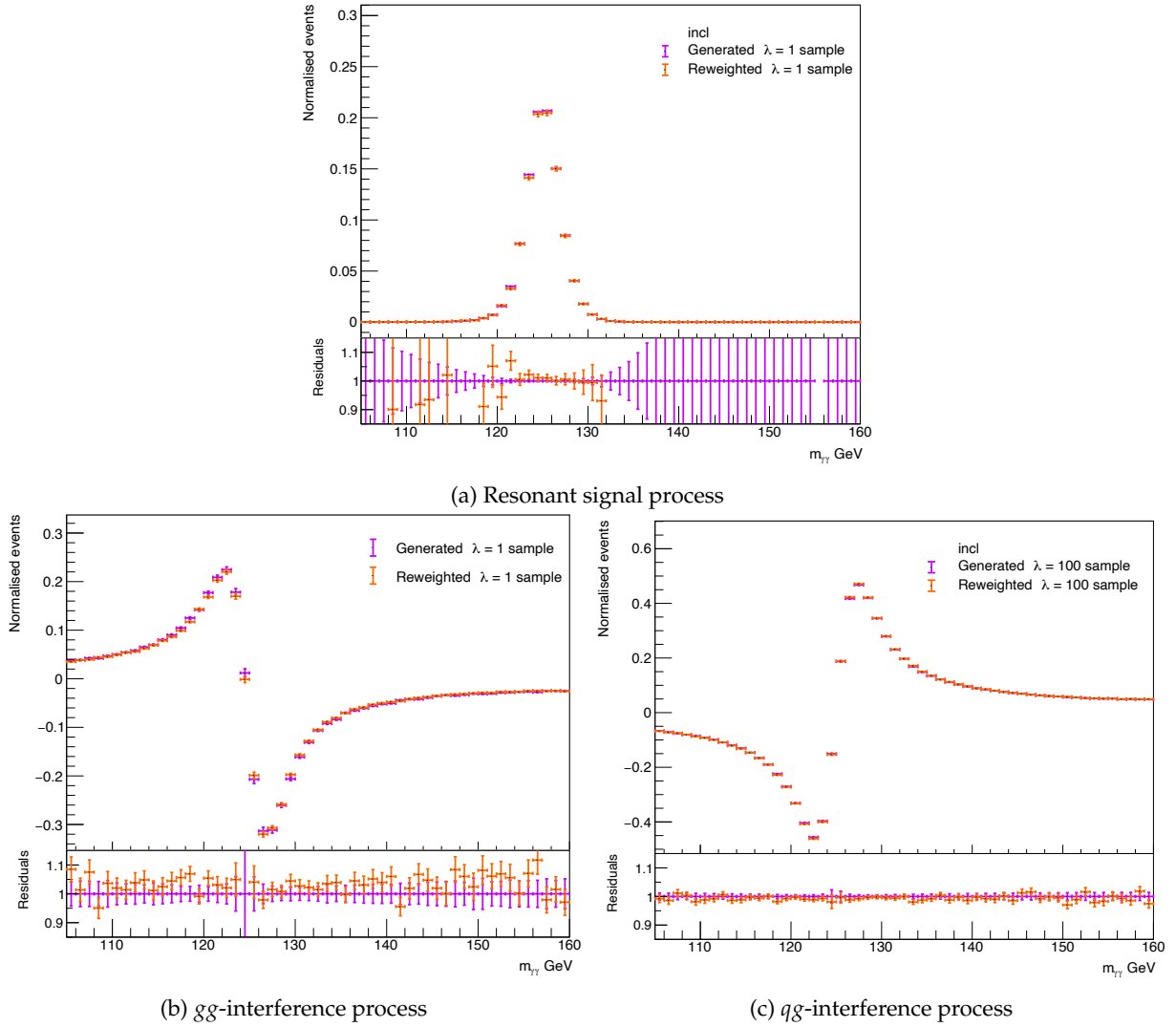


Figure 6.5: Comparison between the official $m_{\gamma\gamma}$ distributions generated at reconstruction level, and those obtained via the reweighting procedure. The signal and gg -interference use the generated $\lambda = 1$ sample to do the re-weighting validation (since they both use $\lambda = 100$ MC to perform the re-weighting), whilst the qg -interference uses a $\lambda = 100$ generated sample for the validation since in this case the $\lambda = 1$ is used for the procedure.

the longitudinal segmentation of the calorimeter (‘pointing’). The diphoton primary vertex is defined by the algorithm as the one receiving the highest score.

The algorithm was initially developed for Run 1 $H \rightarrow$ analyses [111], and has since been updated using a boosted decision tree (BDT) algorithm to be more optimal for other Higgs boson production modes [112], as well as the higher pileup environment present during the Run 2 data-taking period. The same variables are used in this re-training, as were used for the NN algorithm. The efficiency of this updated algorithm is shown in Figure 6.6 as a function of the Higgs boson p_T^H for the ggH Higgs boson production mode, within a 0.3 mm window along the beam pipe from the pp interaction point. Once the diphoton PV is defined, the position of the two leading photons is recalculated by defining a straight line connecting this PV with the centre of the corresponding cluster in the first layers of the calorimeter; this is used to redefine the photon η variable. The selection criteria applied to the two leading photons defining the PV is detailed in section 6.3.2.

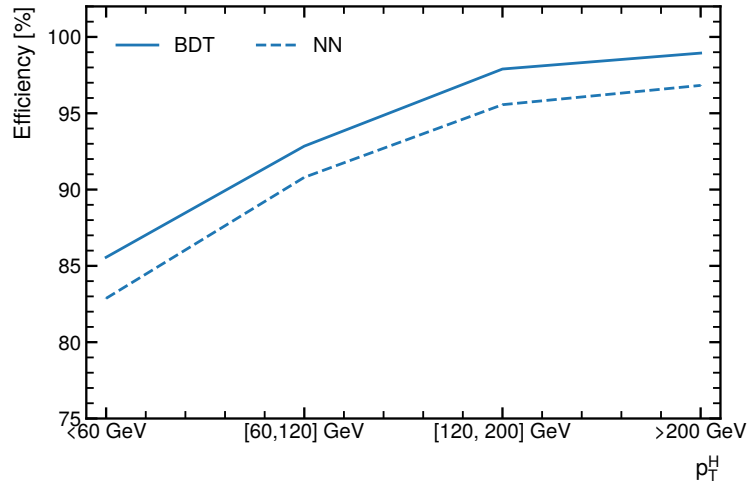


Figure 6.6: Diphoton primary vertex selection efficiency using the NN algorithm compared to the re-trained BDT, as a function of the Higgs boson transverse momentum [113].

6.3.2 Event selection

The event selection criteria for the $H \rightarrow \gamma\gamma$ analysis are as follows. Details of the photon identification and isolation criteria can be found in section 5.4.

- **Trigger (2015 and 2016 data):** Events recorded during 2015 and 2016 must have fired the HLT_g35_loose_g25_loose diphoton trigger which is used to obtain ≥ 2 reconstructed photons passing the *loose* identification requirement.
- **Trigger (2017 and 2018 data):** Events recorded during 2017 and 2018 must have fired the HLT_g35_medium_g25_medium_L12EM20VH diphoton trigger which is used to obtain ≥ 2 reconstructed photons passing the *medium* identification requirement.

- **Good Run List:** Events must belong to a predefined set of ATLAS Good Run Lists, which require all sub-detectors to be on and fully operational.
- **Data Quality:** Standard data quality criteria are applied on data and MC simulated events to ensure all parts of the detector are present, and there are no data integrity issues from any sub-detectors.
- **Two loose photons:** Events must contain at least two photons which pass the offline *loose* identification criteria. These pre-selected photons must also satisfy $p_T > 25 \text{ GeV}$, and $|\eta| < 2.37$, but not fall in the calorimeter barrel and end-cap transition region defined between $1.37 < |\eta| < 1.52$.
- **Has a PV:** There must be at least one reconstructed diphoton primary vertex in the event, which by construction contains the two final state photon candidates. These two photons are labelled as the leading and subleading photons (leading corresponds to the highest energy), which define the diphoton final state of the $H \rightarrow \gamma\gamma$ decay.
- **Trigger matching:** Reconstructed photon candidates must correspond to objects having fired the High-Level Trigger (HLT).
- **Tight γ ID:** The two pre-selected photons must both pass the *tight* identification criteria, as defined in section 5.4.1.
- **Isolation:** The two photons must also satisfy the following isolation criteria associates to calorimeter isolation, E_T^{iso} , and track isolation, p_T^{iso} :

$$E_T^{\text{iso}} \Big|_{\Delta R < 0.2} < 0.065 \cdot p_T \quad \text{and} \quad p_T^{\text{iso}} \Big|_{\Delta R < 0.2} < 0.05 \cdot p_T ;$$

where each of E_T^{iso} and p_T^{iso} are determined within a cone of radius $R = 0.2$ around the directional vector for each photon. These isolation requirements are used to mitigate background events, for example deriving from neutral meson decays to a pair of photons, as well as pileup causing mis-identification.

Only events where the photons are associated to the PV, both are isolated, and both pass the tight criteria are selected; all other events are rejected.

- **Relative p_T cuts:** The leading (γ_1) and subleading (γ_2) photons must pass $p_T^{\gamma_1} / m_{\gamma\gamma} > 0.35$ and $p_T^{\gamma_2} / m_{\gamma\gamma} > 0.25$ respectively.
- **$m_{\gamma\gamma}$ mass window:** The diphoton invariant mass is required to be in the range $m_{\gamma\gamma} \in [105 \text{ GeV}, 160 \text{ GeV}]$, where the invariant mass is defined as:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)} , \tag{6.15}$$

Year Selection cut	2015			2016		
	Events	Tot. eff. [%]	Rel. eff. [%]	Events	Tot. eff. [%]	Rel. eff. [%]
All events	26684852	100.00	-	221203552	100.00	-
GRL	26074048	97.71	97.71	216177760	97.73	97.73
Pass trigger	25823600	96.77	99.04	208625888	94.31	96.51
Data quality	25821064	96.76	99.99	208619936	94.31	100
Has PV	25820988	96.76	100	208619904	94.31	100
2 loose photons	3614494	13.55	14	36496988	16.50	17.49
Trigger matching	2671858	10.01	73.92	27422184	12.40	75.14
Tight γ ID	376969	1.41	14.11	3687766	1.67	13.45
Isolation	151476	0.57	40.18	1464740	0.66	39.72
Rel. p_T cuts	131391	0.49	86.74	1271547	0.57	86.81
$m_{\gamma\gamma} \in [105, 160]$ GeV	28746	0.11	21.88	283205	0.13	22.27

Table 6.3: Number of events remaining in 140 fb^{-1} of data after each event selection criterion is applied to 2015 and 2016 datasets. The relative efficiency is calculated as the efficiency with respect to the previous selection applied.

where E_1 and E_2 are the energies of the leading and subleading photons; and θ , the angle between the two photons.

Tables 6.3 and 6.4 present the number of events remaining after each of the above selections are applied to the data, starting from the total number of recorded events in the PhysicsMain data stream. The number of events at each stage in the selections have been listed separately for each of the data-taking years. In total, around 1.1 million data events pass the selection criteria. The column labelled ‘Rel. eff.’ corresponds to the relative efficiency of each selection, calculated by the percentage difference of that specific selection with respect to the previous selection applied.

Tables 6.5 and 6.6 reports the expected number of events at each stage in the selection criteria for the $m_H = 125 \text{ GeV}$, and $\lambda = 1$ MC samples for the resonant signal, and two interference contributions respectively. Note that the total number of events for the gg -interference is negative as expected given that the theoretically predicted cross-section for this process is negative. The final $m_{\gamma\gamma}$ selection applied to the gg -interference sample (the final line in Table 6.6) actually results in an increase of events compared to the penultimate selection applied. This is due to the unique shape of the gg -interference $m_{\gamma\gamma}$ distribution, which is explained more thoroughly by the investigation presented in Appendix A.

6.4 Event categorisation

Events which pass these selection criteria defined in section 6.3, are then further classified in reconstructed categories. These categories are usually defined with the intention of enhancing particular features in the data, for example a region with particularly good $m_{\gamma\gamma}$ resolution, different signal over background ratios, or targetting a specific Higgs boson production mode. Unlike

Year Selection cut	2017			2018		
	Events	Tot. eff. [%]	Rel. eff. [%]	Events	Tot. eff. [%]	Rel. eff. [%]
All events	213511216	100.00	-	268678208	100.00	-
GRL	207136448	97.01	97.01	265452832	98.80	98.80
Pass trigger	185083728	86.69	89.35	239147840	89.01	90.09
Data quality	185054416	86.67	99.98	239135264	89	99.99
Has PV	185054416	86.67	100	239135264	89	100
2 loose photons	21857452	10.24	11.81	28374150	10.56	11.87
Trigger matching	13441074	6.30	61.49	18743580	6.98	66.06
Tight γ ID	4624282	2.17	34.40	6409828	2.39	34.20
Isolation	1852435	0.87	40.06	2485239	0.92	38.77
Rel. p_T cuts	1606093	0.75	86.70	2156352	0.80	86.77
$m_{\gamma\gamma} \in [105, 160]$ GeV	370335	0.17	23.06	496814	0.18	23.04

Table 6.4: Number of events remaining in 140 fb^{-1} of data after each event selection criterion is applied to the 2017 and 2018 datasets. The relative efficiency is calculated as the efficiency with respect to the previous selection applied.

Production mode Selection cut	ggH		
	Exp. events	Tot. eff. [%]	Rel. eff. [%]
All events	11009.57	100.00	-
GRL	11009.42	100.00	100.00
Pass trigger	7214.50	65.53	65.53
Data quality	7214.50	65.53	100.00
Has PV	7214.50	65.53	100.00
2 loose photons	5922.31	53.79	82.09
Trigger matching	5447.91	49.48	92.04
Tight γ ID	4823.70	43.81	88.54
Isolation	4284.45	38.92	88.82
Rel. p_T cuts	3985.55	36.20	93.02
$m_{\gamma\gamma} \in [105, 160]$ GeV	3984.49	36.19	99.97

Table 6.5: Expected number of events remaining in 140 fb^{-1} of data after each selection criterion is applied to the sample of $gg \rightarrow H \rightarrow \gamma\gamma$ MC simulated events. The relative efficiency is calculated as the efficiency with respect to the previous selection applied.

Production mode Selection cut	gg-interference			qg-interference		
	Exp. events	Tot. eff. [%]	Rel. eff. [%]	Exp. events	Tot. eff. [%]	Rel. eff. [%]
All events	-130.87	100.00	-	11.59	98.14	-
GRL	-130.87	100.00	100.00	11.59	98.14	100.00
Pass trigger	-116.87	89.30	89.30	11.81	100.00	101.90
Data quality	-116.87	89.30	100.00	11.81	100.00	100.00
Has PV	-116.88	89.31	100.01	11.81	100.00	100.00
2 loose photons	-97.48	74.49	83.40	9.87	83.54	83.54
Trigger matching	-98.34	75.14	100.88	10.95	92.74	111.12
Tight γ ID	-91.06	69.58	92.60	10.47	88.64	95.57
Isolation	-85.91	65.65	94.34	10.57	89.51	100.98
Rel. p_T cuts	-64.88	49.58	75.52	7.85	66.50	74.30
$m_{\gamma\gamma} \in [105, 160]$ GeV	-70.96	54.22	109.37	8.87	75.10	112.93

Table 6.6: Expected number of events remaining in 140 fb^{-1} of data after each selection criterion is applied to the sample of gg - and qg -interference MC simulated events. The relative efficiency is calculated as the efficiency with respect to the previous selection applied.

the event selection, which follows a common procedure amongst ATLAS $H \rightarrow \gamma\gamma$ analyses, the definition of reconstructed categories is entirely analysis specific, focussing on properties unique to the given process or observable of interest. In this analysis specifically, we want to define regions which enhance the ultimate sensitivity to the Higgs boson width parameter of interest, $\lambda = \Gamma_H/\Gamma_{\text{SM}}$. This section describes the procedure used to define the event categories for this analysis.

What we define as the *optimal* categorisation scenario for this analysis is primarily based on two factors:

- The sensitivity to λ , the parameter of interest (POI) for this analysis. This is primarily achieved by defining orthogonal categories that simultaneously maximise the sensitivity to the interference effects whilst minimising the continuum background contribution.
- Ensuring the regions in phase space defined by the categories are sufficiently populated by both the signal and the two interference contributions; if the yield is too low in any given category this affects the stability of the fit used to extract the POI.

The main strategy is to exploit the strong dependence of the peak mass shift in the $m_{\gamma\gamma}$ distribution due to interference effects, on a cut on the Higgs transverse momentum p_T^H , as illustrated in Figure 3.13 and discussed in Chapter 3.3. Two or more exclusive p_T regions can be defined with appropriate requirements on the $p_T^{\gamma\gamma}$ of the selected events, thus creating at least one low- p_T category targeting a region of the phase-space highly affected by the presence of interference and other high- p_T categories where the mass shift is expected to be negligible.

The $p_T^{\gamma\gamma}$ distributions of the signal, gg -interference and qg -interference samples are shown in Figure 6.7 - 6.9 respectively, where the majority of the signal and gg -interference events have $p_T^{\gamma\gamma} \lesssim 50$

GeV. Note cross-section for the gg -interference is negative; the $p_T^{\gamma\gamma}$ distribution for gg -interference events is entirely negative. This alone of course is unphysical, however the interference only physically exists when both the signal and background processes are present.

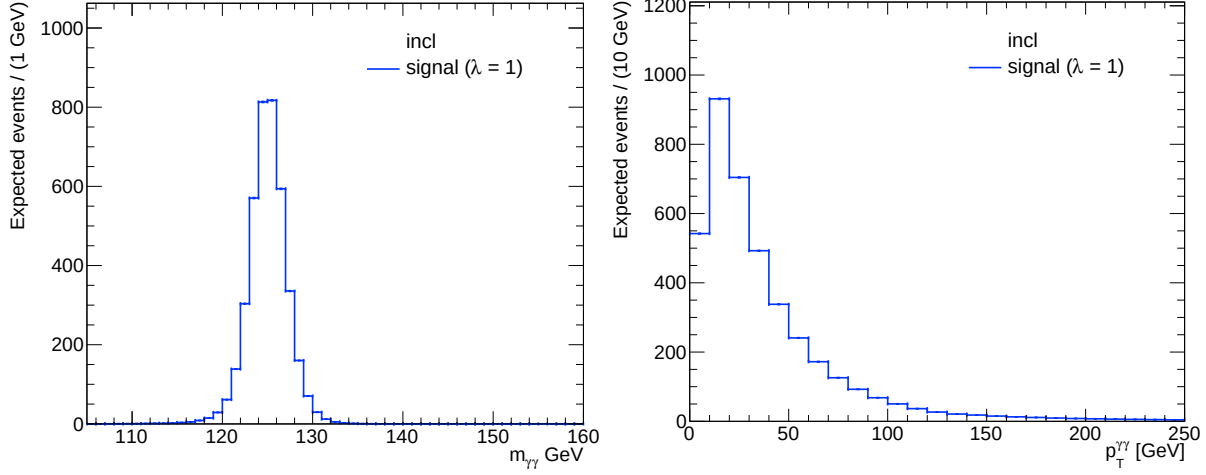


Figure 6.7: Distributions of $m_{\gamma\gamma}$ (left) and $p_T^{\gamma\gamma}$ (right) for the signal after the diphoton event selection.

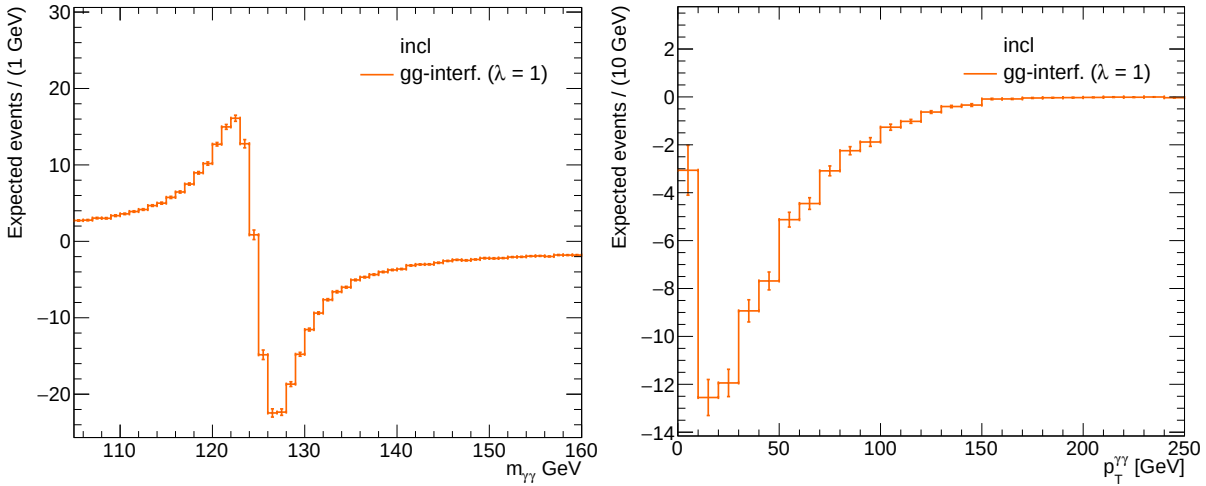


Figure 6.8: Distributions of $m_{\gamma\gamma}$ (left) and $p_T^{\gamma\gamma}$ (right) for the gg -interference after the diphoton event selection.

The limiting factor when choosing regions defined by different $p_T^{\gamma\gamma}$ selections, is the poor agreement between different parton showering algorithms in Sherpa. This has been studied by the Sherpa authors and is illustrated in Figure 6.10; this discrepancy is under investigation. Consequently, selections on $p_T^{\gamma\gamma}$ should only be defined in the low- $p_T^{\gamma\gamma}$ region, where good agreement is observed between alternative parton showering algorithms. This is evident in Figure 6.10 when comparing the dashed line corresponding to the CS shower prediction, with the dash-dotted line illustrating the Dire shower prediction, which overlap only in the very low $p_T^{\min}$ region. The advice received by the Sherpa authors is to use a maximum selection value of $p_T^{\gamma\gamma} = 40$ GeV, although

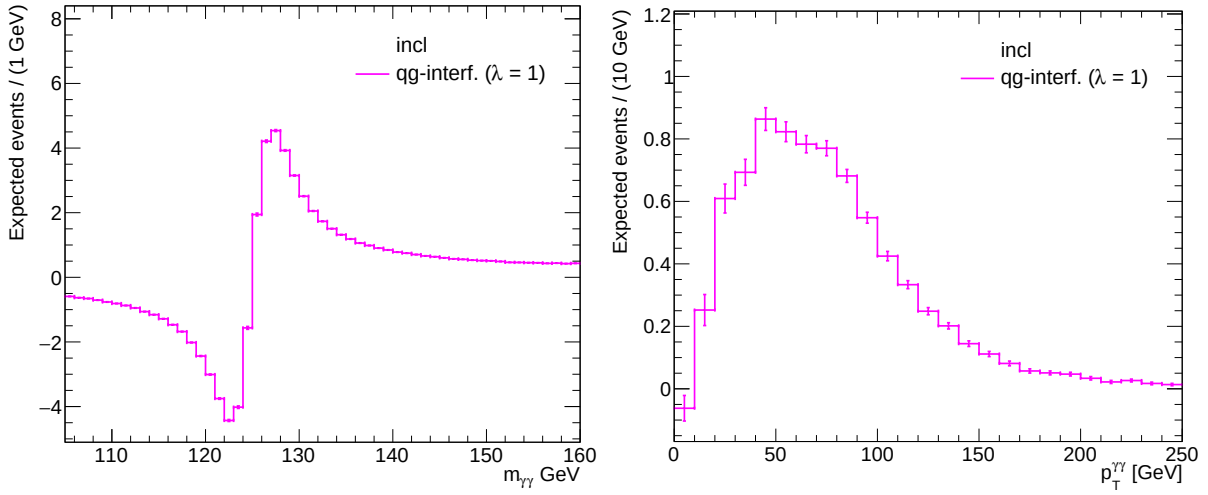


Figure 6.9: Distributions of $m_{\gamma\gamma}$ (left) and $p_T^{\gamma\gamma}$ (right) for the qg -interference after the diphoton event selection.

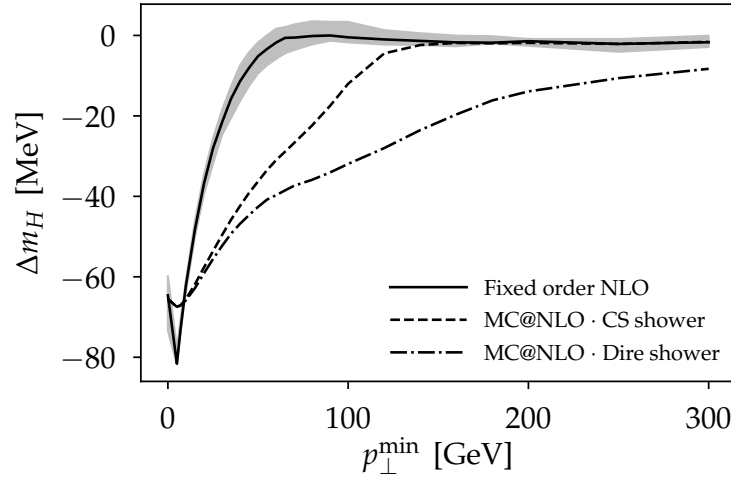


Figure 6.10: Distribution of the shift in the diphoton invariant mass peak due to the interference effects, as a function of the lower cut on the Higgs boson's transverse momentum. This distribution has been evaluated at fixed order (NLO) in Sherpa (solid line), with the CataniSeymour shower algorithm (dashed line) and the Dire shower algorithm (dash-dotted line) [114]. Good agreement is only observed between showering algorithms in the low $p_T^{\min}$ region.

$p_T^{\gamma\gamma} = 30$ GeV is more ideal. Below this value, there is the possibility to define multiple $p_T^{\gamma\gamma}$ regions. This will affect the choice of event categories to be used in the analysis, as there should be no categories defined that further divide the high- p_T region (where ‘high’ means $p_T^{\gamma\gamma} = 40$ GeV). The final selections chosen will be decided following the optimisation study detailed in section 6.4.1.

To improve the signal-to-background ratio, events could be further split into a *central*, *outer-barrel*, or *forward* region according to the pseudorapidity $|\eta|$ of the two photons: if both photons have

$|\eta| < 0.8$, the event is classified as *central*; if either one of the photons has $|\eta| > 0.8$ and both photons have $|\eta| < 1.37$ the event is classified as being in the *outer-barrel*, otherwise if at least one photon has $|\eta| \geq 1.52$, the event is *forward*. This will be investigated in section 6.4.1 to understand the effect on the analysis sensitivity to the Higgs boson width POI, λ .

6.4.1 Optimisation studies

Given the considerations mentioned above, the following four categorisation scenarios have been investigated. The selections defining these scenarios are based on photon kinematics:

- $p_T^{\gamma\gamma}$, the transverse momentum of the diphoton system;
- $|\eta_{\gamma_1}|$ ($|\eta_{\gamma_2}|$), the pseudorapidity of the leading (subleading) photon;
- the conversion type of the two photons, which exactly matches the calibration definition: *UU* denotes both leading and subleading photons are unconverted, *UC* instead means one of the two photons are converted.

The four categorisation scenarios are defined as:

- **Scenario 0:** 2 categories in $p_T^{\gamma\gamma}$ defined by a low $p_T^{\gamma\gamma}$ region with $p_T^{\gamma\gamma} < 30$ GeV, and a high $p_T^{\gamma\gamma}$ region with $p_T^{\gamma\gamma} \geq 30$ GeV.
- **Scenario 1:** 2 categories in $p_T^{\gamma\gamma}$ defined by a low $p_T^{\gamma\gamma}$ region with $p_T^{\gamma\gamma} < 40$ GeV, and a high $p_T^{\gamma\gamma}$ region with $p_T^{\gamma\gamma} \geq 40$ GeV.
- **Scenario 2:** 5 categories in $p_T^{\gamma\gamma}$ defined with the following selections: $p_T^{\gamma\gamma} < 10$ GeV, $10 \leq p_T^{\gamma\gamma} < 20$ GeV, $20 \leq p_T^{\gamma\gamma} < 30$ GeV, $30 \leq p_T^{\gamma\gamma} < 40$ GeV, $p_T^{\gamma\gamma} \geq 40$ GeV.
- **Scenario 3:** 12 categories in total defined by splitting events firstly in terms of $p_T^{\gamma\gamma}$ ($p_T^{\gamma\gamma} < 30$ GeV, or $p_T^{\gamma\gamma} \geq 30$ GeV), then further selecting on pseudorapidity to classify the event as being either in the central, outer-barrel or forward region, and finally splitting according to the photon conversion status (classified as either *UU* or *UC*).

The motivation behind defining these categorisation scenarios as such is as follows. Scenario 0 is initially chosen as the baseline approach for the analysis, exploiting the dependence of interference effects on $p_T^{\gamma\gamma}$. The cut value was recommended by the Sherpa authors (specifically Stefan H  eche and Enrico Bothmann), as previously mentioned. An alternate cut value of 40 GeV was chosen to define Scenario 1, to study the dependence of the sensitivity to λ on this cut value. Additional binning in the low- $p_T^{\gamma\gamma}$ regime where the interference effects are large may bring additional sensitivity to λ . Including pseudorapidity and conversion status cuts for Scenario 3 attempts to improve the signal-to-background ratio.

The category optimisation has been undertaken by evaluating the impact of each categorisation on the final sensitivity to λ , the procedure proceeds as follows. A simplified version of the model

described in section 6.9 is used to fit an Asimov dataset generated at $\lambda = 1$. For these studies, the signal and interference components were modelled using the procedure described in section 6.5 and section 6.6 respectively. A simplified background modelling approach is used to fit the background to data in the two sideband regions with a first order exponential function. The two free parameters for the analytical background model are the overall background normalisation, N_{bkg} , and the shape of the exponential, parametrised by α . The additional simplification used here with respect to the model described in section 6.9 is that no systematic uncertainties are included for these categorisation studies. A likelihood scan is then performed over λ to extract the upper limit on λ at the 95% C.L. The value of this upper limit is used to probe the sensitivity to λ and therefore quantify which category scenario results in the most accurate determination of λ . These scans are repeated for three different fit configurations, where in addition to evaluating the likelihood at different λ values, the μ and also m_H parameters are profiled over. The resulting upper limits for each of these fit configurations, in each of the four proposed event category scenarios are reported in Table 6.7. The different configurations of the statistical model considered:

1. λ is the only free-to-float POI, while the signal strength parameter and the Higgs boson mass are set to the SM values, $\mu = 1$ and $m_H = 125.09$ GeV, respectively;
2. λ is the free-to-float POI and μ is profiled, whilst the Higgs boson mass is set to $m_H = 125.09$ GeV;
3. λ is the free-to-float POI, μ and m_H are profiled where m_H is implemented as a Gaussian constrained value defined by $m_H = 125.09 \pm 0.24$ GeV where this value is taken from the Run 1 combined ATLAS+CMS Higgs mass measurement in the combined $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$ channels [115].

Configuration 1 is more dependent on assumptions, than configuration 2, which is in turn more dependent than configuration 3. For each of these three configurations, a likelihood scan was performed over $\lambda \in [0, 200]$ with a step size of 1. When plotting the profile likelihood, the crossing at $-2\ln\Gamma = 3.84$ is used as a proxy for the upper limit (UL) at 95% CL. The upper limits for each of the three configurations, for each of the four event categorisation scenarios, are presented in Table 6.7a - 6.7d. The likelihood scans corresponding to the results detailed in Table 6.7a - 6.7d are shown in Figure 6.11.

When profiling over both μ and m_H , the category choice most sensitive to λ is Scenario 1; this is $\mathcal{O}(10)\%$ better than the sensitivity achieved with Scenario 0. There is only a very slight difference observed between Scenario 0 and 2, 1.6%, i.e. it makes little difference defining the $p_T^{\gamma\gamma}$ cut at 30 GeV or 40 GeV. Also between Scenario 0 and Scenario 3 the difference in sensitivities is small, with a 4.2% improvement for Scenario 3 over Scenario 0. These differences are all reduced by 1 – 2% when either only λ is free-to-float, or also μ is profiled over.

Parameters to float or profile over	U.L. on λ at 95%C.L.	U.L. on Γ_H
λ	79.2	323.9 MeV
λ, μ	80.2	328.0 MeV
λ, μ, m_H	126.3	516.6 MeV

(a) Scenario 0 sensitivity results

Parameters to float or profile over	U.L. on λ at 95%C.L.	U.L. on Γ_H
λ	76.5	312.9 MeV
λ, μ	78.5	321.1 MeV
λ, μ, m_H	124.3	508.4 MeV

(b) Scenario 1 sensitivity results

Parameters to float or profile over	U.L. on λ at 95%C.L.	U.L. on Γ_H
λ	72.6	296.9 MeV
λ, μ	74.4	304.3 MeV
λ, μ, m_H	113.1	462.6 MeV

(c) Scenario 2 sensitivity results

Parameters to float or profile over	U.L. on λ at 95%C.L.	U.L. on Γ_H
λ	72.0	294.5 MeV
λ, μ	74.0	302.7 MeV
λ, μ, m_H	121.0	494.9 MeV

(d) Scenario 3 sensitivity results

Table 6.7: Expected sensitivity in terms of expected upper limit to the λ POI for each of the four proposed event categorisation scenarios. In each case the λ parameter is always floating, while the other parameters (μ and or m_H where applicable) are profiled over.

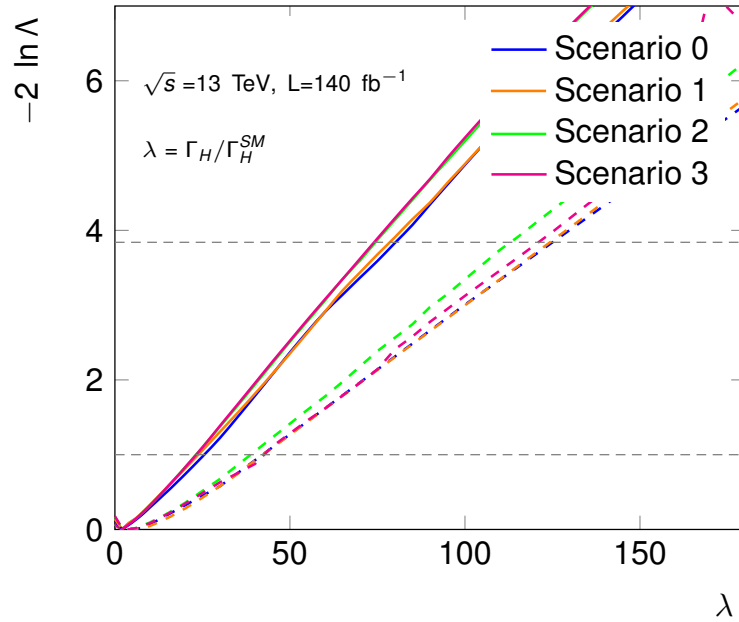


Figure 6.11: Likelihood scans for the four categorisation scenarios. The solid line refers to the results obtained when λ is the free-to-float POI and μ is profiled. The dashed line corresponds to the result obtained when λ is the free-to-float POI, μ and m_H are profiled. For aesthetic simplicity, the configuration choice where both μ and m_H are fixed is not shown, since the results are so close to those of the solid lines for each respective scenario (configuration where μ is profiled). The horizontal grey dashed line at $-2\ln\Lambda = 1$ corresponds to the upper error at 1σ , while the line at $-2\ln\Lambda = 3.84$ is the upper error at 2σ .

6.4.2 Analysis event categorisation

The difference between sensitivities achieved for each of the four scenarios tested was smaller than 10%. Although Scenario 2 provided the best sensitivity, the finer binning resulted in less number of interference events per defined category. This was true even more so for Scenario 3. The categorisation defined by the **Scenario 0** selection criteria was chosen as it is a good compromise in terms of providing the best sensitivity to the λ POI, and the minimal number of total categories. Maintaining a relatively low total number of categories has a higher chance of resulting in a more stable fit, particularly when including the large number of experimental systematic uncertainties, which are also evaluated separately for each reconstructed category. Despite the very small improvement seen for Scenario 1 with respect to Scenario 0, Scenario 0 was chosen to stay in the region of $p_T^{\gamma\gamma}$ indicated by the theorists as being well-modelled.

Given the results and considerations, Scenario 0 is chosen as the baseline categorisation for this analysis. The low- $p_T^{\gamma\gamma}$ region, defined by selecting $p_T^{\gamma\gamma} < 30$ GeV is labelled as ‘Cat1’, whilst the second category with $p_T^{\gamma\gamma} \geq 30$ GeV is labelled ‘Cat2’. The $m_{\gamma\gamma}$ distributions in each of these two Scenario 0 categories are shown in Figure 6.12 for the signal, gg -interference and qg -interference components. The difference in interference effects between these two categories is not immediately obvious, since the mass shift due to the real part of the interference is on the order of 0.1 GeV or lower, compared to the 55 GeV mass range displayed. Figures 6.13a and 6.13b

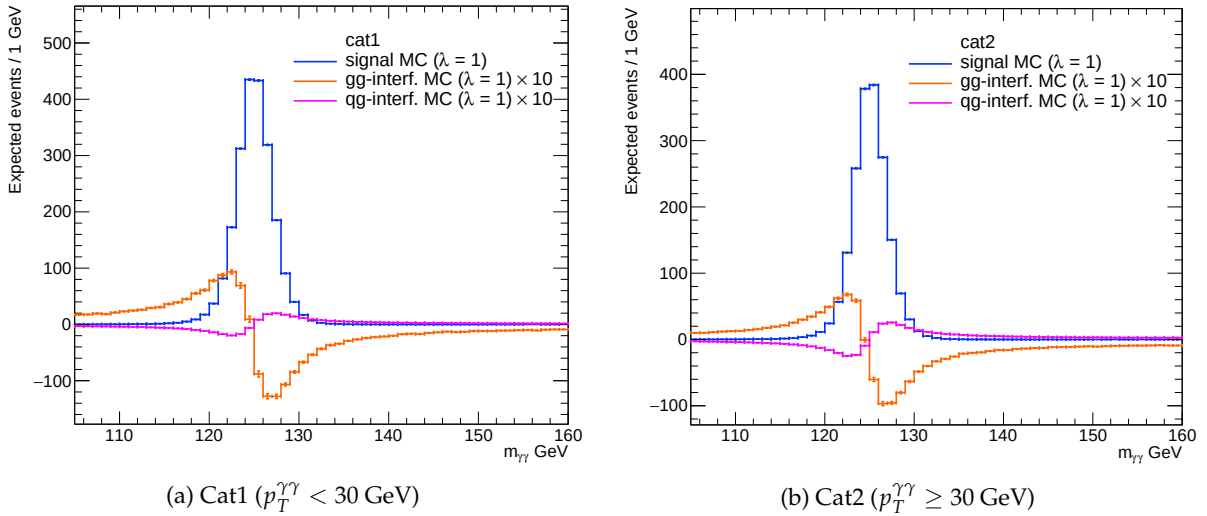


Figure 6.12: Distributions of $m_{\gamma\gamma}$ for the Higgs boson signal (black), gg -interference (red) and qg -interference (pink) in 6.12a category 1 ($p_T^{\gamma\gamma} < 30$) and 6.12b category 2 ($p_T^{\gamma\gamma} \geq 30$). The gg -interference and qg -interference components are rescaled by a factor 10 for visualisation purposes.

display the signal, and signal plus interference $m_{\gamma\gamma}$ distributions for category 1 and category 2 respectively. This mass shift can then be calculated in each category by taking the difference in the first moment of each distribution, per category. These values are summarised in Table 6.8, where the mass shift in the inclusive region (so no selection on applied) is also listed. As a

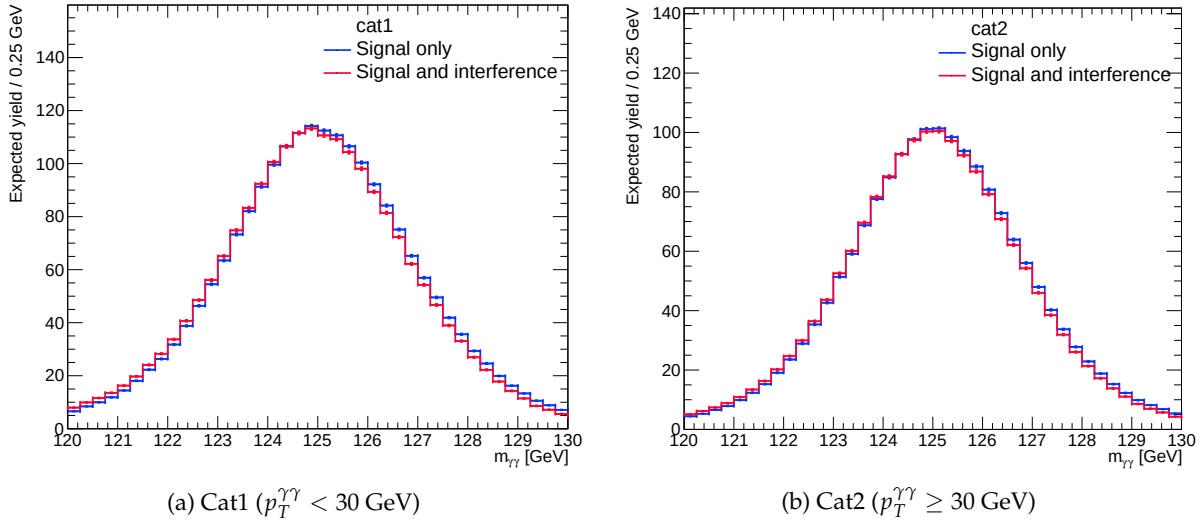


Figure 6.13: Distributions of $m_{\gamma\gamma}$ for the signal process only (red), and the signal plus interference processes (blue) in 6.13a category 1 ($p_T^{\gamma\gamma} < 30$) and 6.13b category 2 ($p_T^{\gamma\gamma} \geq 30$). The interference included here consists of both the gg -interference and qg -interference components.

side-note, it may be interesting to know that the mass shift in the region $p_T^{\gamma\gamma} \geq 150$ GeV is just 3.2 MeV, which agrees with the theoretically expected behaviour of having less interference effects as the minimum $p_T^{\gamma\gamma}$ requirement increases. The values reported in Table 6.8 correspond to those evaluated using $\lambda = 1$ simulated events, where the relative difference in the mass shift between the two categories is 16.4 MeV. As discussed in section 3.3.4, this mass shift varies as a function of the Higgs boson width, Γ_H . This dependency has been evaluated using simulated events at various Higgs boson width values, and is displayed in Figure 6.14.

Category	$\Delta m_{\gamma\gamma}$ [MeV]
Inclusive	61.9
Cat1	69.3
Cat2	52.9

Table 6.8: Expected mass shift, $\Delta m_{\gamma\gamma}$, for each analysis category, and the inclusive case (where no additional selections are applied). The interference component used to define the signal plus interference distribution consists of both the gg - and qg - processes at NLO.

The expected events yields for 140 fb^{-1} are listed in Table 6.9, where the number of signal (N_S), gg -interference ($N_{I(gg)}$), qg -interference ($N_{I(qg)}$) and background (N_B) events are reported. N_S , $N_{I(gg)}$ and $N_{I(qg)}$ are computed directly from the respective MC samples. N_B is estimated from fitting the data sideband regions with a first order exponential function, and integrating over $m_{\gamma\gamma} \in [105, 160]$ GeV.

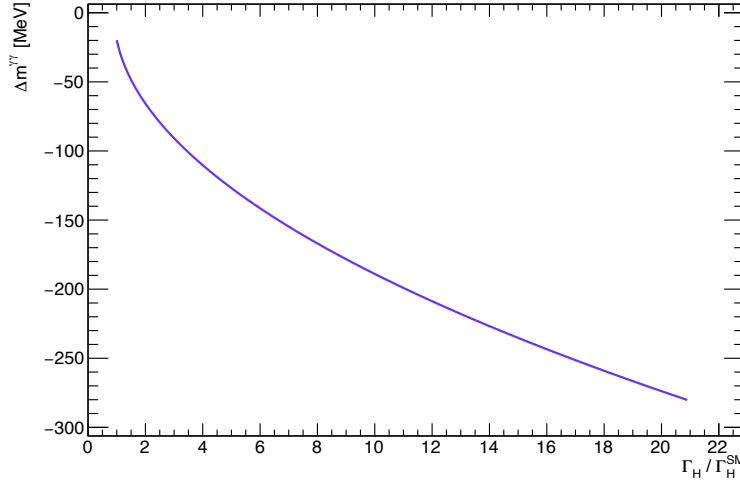


Figure 6.14: Expected mass shift calculated as a function of the Higgs boson width parameter of interest, $\lambda = \Gamma_H / \Gamma_H^{\text{SM}}$.

Category	N_S	$N_{I(gg)}$	$N_{I(qg)}$	N_B
Cat1 ($p_T^{\gamma\gamma} < 30 \text{ GeV}$)	2177.3	-34.9	2.4	$6.66 \cdot 10^5$
Cat2 ($p_T^{\gamma\gamma} \geq 30 \text{ GeV}$)	1806.7	-36.2	6.5	$5.12 \cdot 10^5$

Table 6.9: The expected number of events in 140 fb^{-1} of data for the signal (N_S), gg -interference ($N_{I(gg)}$), qg -interference ($N_{I(qg)}$) and background (N_B) processes in each of the two analysis categories, within the $m_{\gamma\gamma}$ window $[105, 160] \text{ GeV}$.

6.5 Signal model

The shape of the signal, interference, and background $m_{\gamma\gamma}$ distributions are described with analytical functions. This section outlines the functional form and modelling strategy for the resonant signal component. The theoretical resonant lineshape for a decaying Higgs boson is a Breit-Wigner distribution with a peak position corresponding to the Higgs boson mass, m_H , and a narrow resonance width of $\Gamma_H^{\text{SM}} = 4.09 \text{ MeV}$. The diphoton invariant mass distribution observed in data instead is broadened due to the finite resolution with which the detector is able to measure the photon energy and direction in the calorimeter. To describe these effects, the signal is modelled using a double-sided crystal ball (DSCB) function, f_{DSCB} , which allows us to account for the detector resolution effects and asymmetric radiative energy losses. The DSCB is a composite function defined by a central Gaussian core with two separate power law tails, and is conceptually illustrated in Figure 6.15. Using this function to model the Higgs boson signal is recommended for use by all $H \rightarrow \gamma\gamma$ analyses; further details can be found in [110].

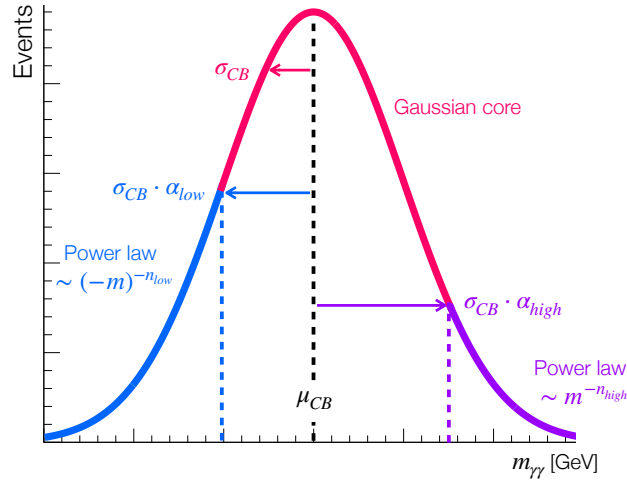


Figure 6.15: Illustration of the double-sided crystal ball function which is characterised by a Gaussian core with two separate power law tails, and is used to model $m_{\gamma\gamma}$. μ_{CB} denotes the mean of the distribution, corresponding to m_H , while the width parameter σ_{CB} represents Γ_H as measured by the detector. The transition regions between the Gaussian core and the power law tail are defined by $\sigma_{CB} \cdot \alpha_{low}$ and $\sigma_{CB} \cdot \alpha_{high}$ either side of the peak.

The DSCB is described by the following normalised function:

$$f_{DSCB}(m_{\gamma\gamma}) = \begin{cases} e^{-\frac{t^2}{2}} & \text{if } -\alpha_{low} \leq t \leq \alpha_{high} \\ \frac{e^{-\frac{1}{2}\alpha_{low}^2}}{\left[\frac{1}{R_{low}}(R_{low}-\alpha_{low}-t)\right]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \frac{e^{-\frac{1}{2}\alpha_{high}^2}}{\left[\frac{1}{R_{high}}(R_{high}-\alpha_{high}+t)\right]^{n_{high}}} & \text{if } t > \alpha_{high} \end{cases}, \quad (6.16)$$

where $t = \frac{(m_{\gamma\gamma} - \mu_{CB})}{\sigma_{CB}}$, $R_{low} = \frac{n_{low}}{\alpha_{low}}$ and $R_{high} = \frac{n_{high}}{\alpha_{high}}$. The total number of parameters describing the DSCB shape is six: μ_{CB} , σ_{CB} , α_{low} , α_{high} , n_{low} and n_{high} . These parameters can be interpreted as:

- μ_{CB} and σ_{CB} are the mean and width of the Gaussian core, interpreted as the Higgs boson mass, m_H and the width of the distribution as measured by the detector;
- n_{low} and n_{high} are the exponents of the power-law tails either side of the peak. These parameters model only the shape of the tails, they do not affect the peak of the distribution since majority of the events are located within the region $\mu_{CB} \pm \sigma_{CB} \cdot \alpha$;
- α_{low} and α_{high} parametrise the transitions between the Gaussian core and the two tails either side of the peak. The exponential tails begin for values that differ from the peak by $\sigma_{CB} \cdot \alpha$ (where α is either α_{low} or α_{high} depending on which side of the peak).

The signal modelling strategy is such that the DSCB function with all six parameters floating is fitted to the nominal signal MC sample, in the range $m_{\gamma\gamma} \in [105 \text{ GeV}, 160 \text{ GeV}]$, separately for each reconstruction category. Following this, the fitted α_{low} , α_{high} , n_{low} and n_{high} parameters are fixed,

and subsequently used as constants in the analysis. The result of fitting the nominal signal sample with a DSCB function, for each of the analysis categories, is shown in Figure 6.16. The chi-square test is used as the criterion to evaluate the goodness of the fit between the MC distribution and the DSCB function. The reduced χ^2 (chi-square value per degree of freedom) is reported in the upper right hand corner of each distribution shown in Figure 6.16. The bottom panel of each texture displays the distribution of residuals, which does have some structure around the peak region. This shape has been observed in previous analyses, where several other possible functions were checked to see if they modelled the signal distribution more accurately. This slight non-closure between the model and the MC is accounted for in the signal modelling uncertainty; the procedure used to estimate this is outlined in section 6.8.7. The six DSCB parameter values obtained, for each category, are listed in Table 6.10.

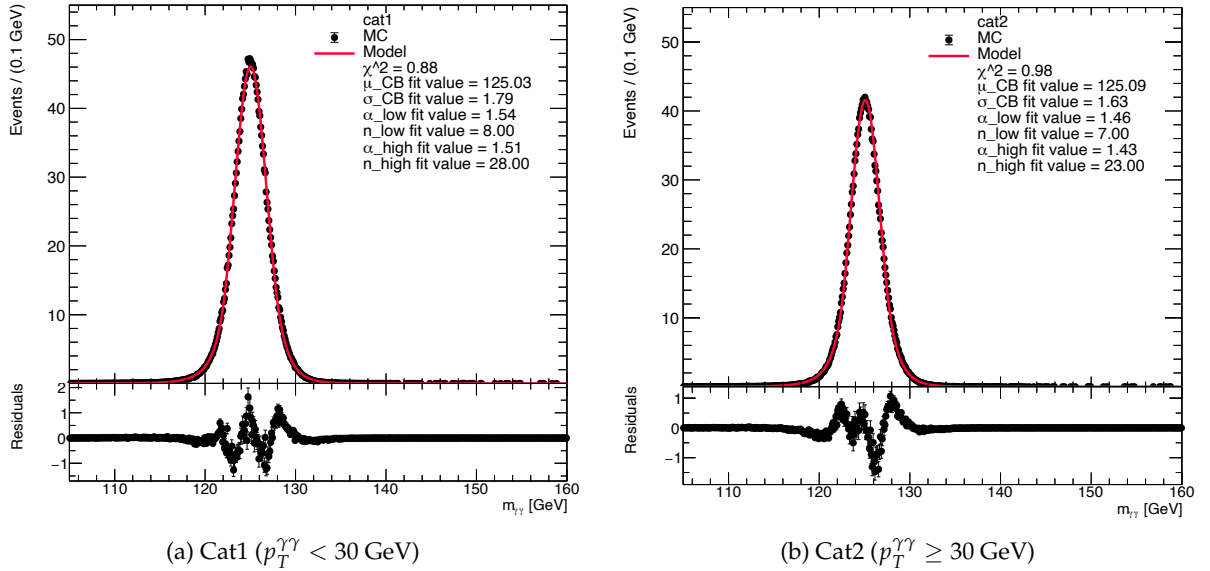


Figure 6.16: DSCB model fitted to MC simulated data for all analysis categories.

Category	μ_{CB} [GeV]	σ_{CB} [GeV]	α_{low}	n_{low}	α_{high}	n_{high}
Cat1	125.03	1.79	1.54	8.00	1.51	28.00
Cat2	125.09	1.63	1.46	7.00	1.43	23.00

Table 6.10: DSCB shape parameters obtained from fitting the SM signal MC sample ($m_H = 125$ GeV, $\lambda = 1$) with a DSCB function (as defined by equation 6.5), for the two analysis categories.

Since m_H and λ directly correspond to the signal shape parameters μ_{CB} and σ_{CB} , these will be allowed to freely vary in the fit, while the other four DSCB parameters remained fixed. This is to reduce the complication of the fit, since we know that a slight variation in the Higgs boson mass value, does not change the shape of the rest of the distribution, it affects only the μ_{CB} parameter (and similarly for λ and σ_{CB}). Section 6.5.1 describes how μ_{CB} is parameterised as a function of m_H ;

section 6.5.2 investigates how sensitive the resonant signal process is to variations of the Higgs boson width, and consequentially whether it is actually necessary to allow the σ_{CB} parameter to vary (again with the intention of aiming to keep the fit as simple as possible).

6.5.1 m_H parametrisation

The Run 1 combination of ATLAS and CMS measurements resulted in a Higgs boson mass value of $m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$ [115], where the uncertainty is well below 1%. The relatively small uncertainty on the mass, allows us to use only the nominal MC sample simulated with $m_H = 125 \text{ GeV}$. Since we know experimentally m_H is very close to 125 GeV, the functional form obtained when fitting the nominal SM MC sample is then fixed, and only the μ_{CB} is allowed to vary slightly. The generalisation of the fitted model to any value of m_H (in a small interval close to 125 GeV) is therefore done by simply shifting the μ_{CB} parameter according to:

$$\mu_{CB} = m_H + \mu_{CB}^{\text{SM}} - 125 \text{ GeV}. \quad (6.17)$$

All other DSCB parameters are fixed to the values obtained by fitting the nominal SM signal MC sample (with $m_H = 125 \text{ GeV}$ and $\lambda = 1$). Similar fits were also made of the DSCB function to the MC, for two m_H values, $m_H = 124 \text{ GeV}$ and $m_H = 126 \text{ GeV}$, for each analysis category. No additional structure was observed in the residuals beyond that seen for the $m_H = 125 \text{ GeV}$ case, and the DSCB described well the MC for these alternate m_H distributions.

6.5.2 Sensitivity to the Higgs boson width

Measuring the Higgs boson via the interferometry method is achieved by exploiting the dependence of the interference effects (both changes in shape and yield) as a function of the Higgs boson width, parametrised by λ , as described in section 3.3. The sensitivity of the signal shape to changes in λ are expected to be sub-dominant with respect to the interference effects since as previously mentioned, the width of the resonance signal peak is dominated by detector resolution effects. A quantitative investigation into the effect on the analysis sensitivity, to variations in the signal distribution as a function of λ were undertaken and are presented in Appendix B. The main conclusion being the impact is very small, less than 1% on the final POI, and so varying the signal shape as a function of the Higgs boson width can be safely neglected.

6.6 Interference model

An analytical function is used to fit the $m_{\gamma\gamma}$ invariant mass distribution for the two interference contributions considered in this analysis. The event yield in certain regions of the $m_{\gamma\gamma}$ distribution is negative for both interference contributions, as shown in Figure 3.11b. A regular PDF cannot be used since it must be positively defined at every point.

The function used to describe the interference lineshape is the difference between two Breit-Wigner Fano resonance functions. In general, a Fano resonance is an asymmetric lineshape characteristic of that produced via the interference between a background and resonant signal process. There are four free parameters defining the Fano function, which can be interpreted as the centre of the peak region μ , the amplitude A , the width of the distribution σ , and a shape parameter q . Two Fano functions are required to model the interference contributions in this analysis given the “two peak” structure (one peak and one dip) of the interference lineshape. Given the interference lineshape is defined by two Fano resonance functions, there are eight free parameters in total. The resulting function is thus defined as:

$$I = \frac{A_1(q_1\sigma_1/2 + m_{\gamma\gamma} - \mu_1)^2}{(\sigma_1/2)^2 + (m_{\gamma\gamma} - \mu_1)^2} - \frac{A_2(q_2\sigma_2/2 + m_{\gamma\gamma} - \mu_2)^2}{(\sigma_2/2)^2 + (m_{\gamma\gamma} - \mu_2)^2} \quad (6.18)$$

For each interference contribution, and for each analysis category this function is fitted to the nominal $m_{\gamma\gamma}$ MC distributions, with $m_H = 125$ GeV and $\lambda = 1$. Fits of the lineshape for each analysis category are shown in Figure 6.17 and Figure 6.18 for the gg - and qg interference contributions respectively. Each of these distributions have been normalised to unity. The total yield for each process is included during the definition of the total PDF in the statistical model, which is outlined in section 6.9. Whilst there are some small features in the residual distributions, this

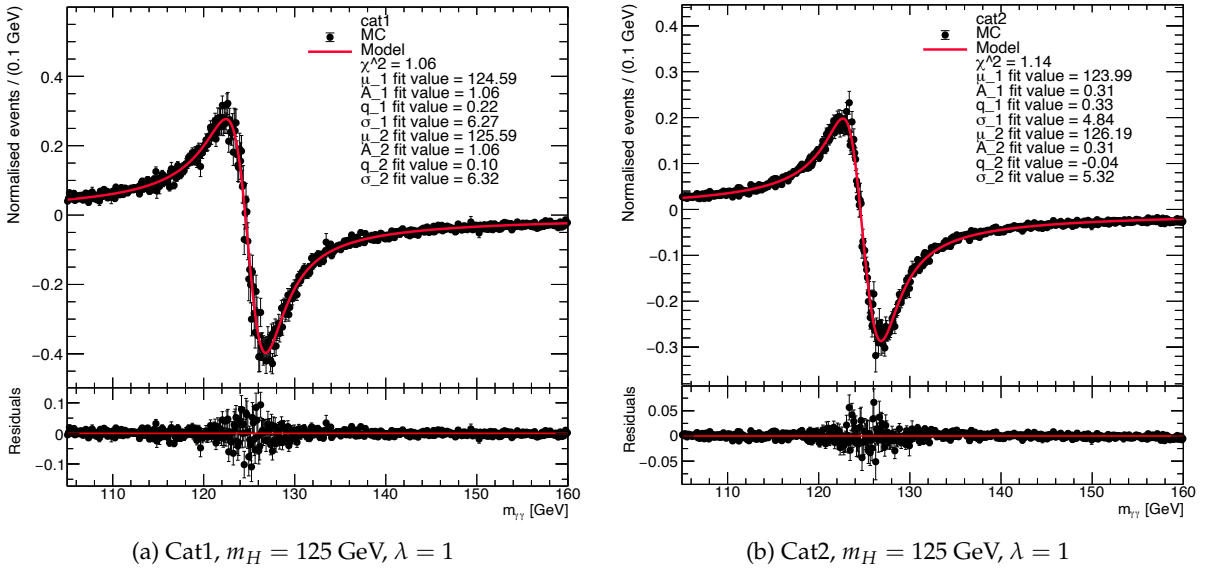


Figure 6.17: Nominal gg -interference $m_{\gamma\gamma}$ invariant mass distributions (shown in black), fitted with the combination of two Breit-Wigner resonance functions (shown in red), for each analysis category

should be covered by the interference modelling uncertainty which assigns an uncertainty based on the mis-modelling between the chosen analytical function and the generated events; this uncertainty will be evaluated in section 6.8.7.

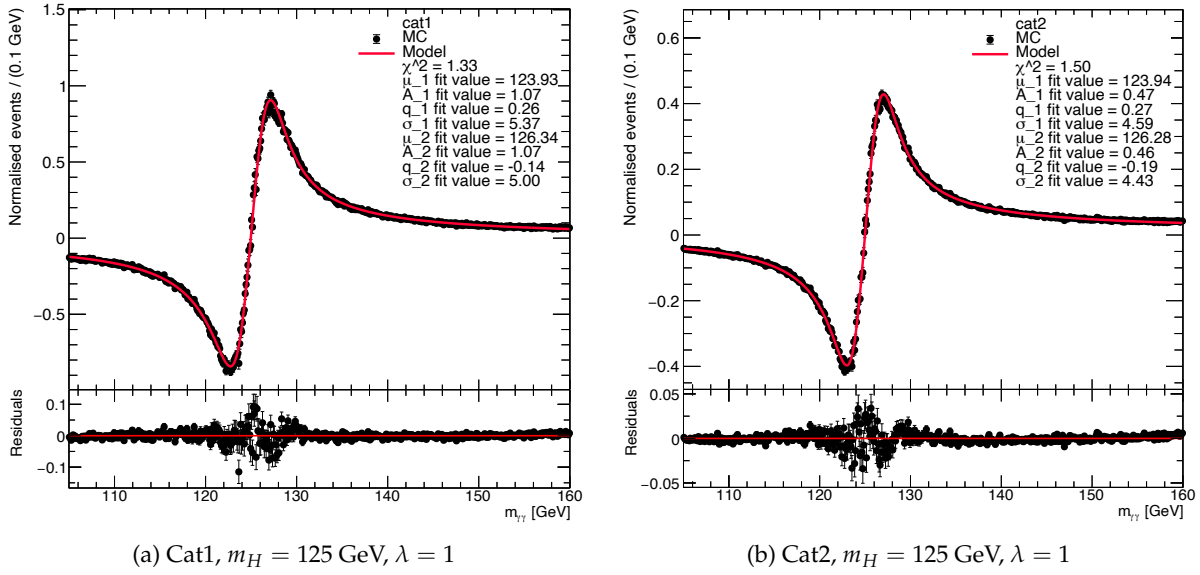


Figure 6.18: Nominal qg -interference $m_{\gamma\gamma}$ invariant mass distributions (shown in black), fitted with the combination of two Breit-Wigner Fano resonance functions (shown in red), for each analysis category

6.6.1 Interference functions with different widths: Morphing

Obtaining samples corresponding to enhanced Higgs boson widths via the reweighting procedure described in section 6.2.3 is appropriate for a small number of alternate distributions. However since it relies on the generation of one additional sample at generator level for each alternative parameter value (be it m_H , λ or otherwise), it does not allow for a continuous description. Additionally, the analytical function which parametrises the interference distributions does not contain parameters that have a direct correspondence to m_H and λ , as is the case for the DSCB signal function via μ_{CB} and σ_{CB} . To obtain a continuous description of the interference functions at any give m_H or λ value, a *moment morphing* method [116] is exploited which is able to interpolate between distribution templates (either histograms or functions) in N -dimensions. In [116] the algorithm definition, construction, and application of the morphing technique to an ATLAS physics analysis used case is detailed. This section will begin with an introduction to moment morphing and what star-morphing is in general, before proceeding to define and validate the star-morphing function as used in this analysis for the interference processes.

Introduction to moment morphing: Particle physics measurements commonly require interpolation between MC generated distributions, to ensure continuity of the relevant parameters of interest. These interpolation techniques can be as simple as a linear parametrisation of a given observable [117], or a more complicated parametrisation of probability density functions, as is implemented in the HistFactory statistical tool [118]. *Moment morphing* is an alternate interpolation

technique which instead uses the first two moments of the distribution to perform the translation¹. The first moment is the mean, μ_{ij} , of some distribution (input template) i , with observable j ; the second moment is the width σ_{ij} . The input functions are shifted by applying a linear transformation to each observable. This is defined for each input distribution/function/PDF i , and each observable j as:

$$x'_{ij} = a_{ij}x_j + b_{ij}, \quad (6.19)$$

where the slope $a_{ij} = \sigma_{ij}/\sigma'_j$, and the offset $b_{ij} = \mu_{ij} - \mu'_j a_{ij}$ are defined in terms of the so-called ‘common’ mean (μ'_j) and width (σ'_j) parameters, meaning common to all distributions. The common mean for the morphing parameter m is defined by:

$$\mu'_j(m) = \sum_i c_i(m) \cdot \mu_{ij}, \quad (6.20)$$

where c_i is the coefficient defined by the distance to the reference template i , and by construction $\sum_i c_i = 1$. Similarly the common width is defined as:

$$\sigma'_j(m) = \sum_i c_i(m) \cdot \sigma_{ij}. \quad (6.21)$$

Equation 6.19 dictates how the observables x_j are modified in order to transform the original function $f(\mathbf{x}|m_i) \rightarrow f(\mathbf{x}'|m_i)$. One advantage of moment morphing is the ability to use both binned histograms as well as continuous functions as inputs. Additionally, the number of input observables, templates or model parameters is not restricted.

A quintessential experimental particle physics analysis requires incorporating systematic uncertainties in the likelihood function, as a series of *up* and *down* variations about a nominal reference template distribution. A specific *star-morphed* function has been developed for this exact use case, where a set of systematic variations are assumed to act individually such that the overall response to the likelihood function is defined by the sum of each set of variations (implemented in the likelihood function as nuisance parameters). This factorisability reduces the number of required inputs for the morphing function to just the nominal reference template, plus an additional two templates (corresponding to the up and down variation), for each systematic uncertainty required². This type of star-morphed PDF has already been successfully used by the $H \rightarrow ZZ^* \rightarrow 4\ell$ mass analysis [119] to include systematic uncertainty variations, in this case for the background components.

Moment morphing is implemented in the RooFit package [120]. The star-morphed function specifically is defined in the RooStarMomentMorph class, which requires as inputs the morphing

¹Note this is true only when a linear transformation is applied to each observable, x_j . A non-linear combination of input templates is also possible in general with moment morphing, but will be omitted from this discussion since it's beyond the scope of the used case.

²In contrast, N unfactorisable systematic variations would require an $N \times N$ grid of reference input distributions.

parameters m , the observables x_j , the list of input reference distributions or functions, and the corresponding parameter values for each input distribution.

Defining the star-morphed function: In general to morph in N -dimensions, the number of reference templates you need as inputs to define the star-morphed function are $1 + 2N$, meaning the nominal sample plus the up and down variation for each morphing dimension. The star-morphing method will be used for the interference contributions to morph over the m_H and λ parameters to obtain a continuous description of the $m_{\gamma\gamma}$ invariant mass distribution between $m_{\gamma\gamma} \in [123 \text{ GeV}, 127 \text{ GeV}]$ and $\lambda \in [1, 400]$. As such, for each interference contribution, five reference input functions are required. This is illustrated in Figure 6.19. In general this morphing function can be easily extended to include also systematic shape variations, where only two additional reference histogram templates are required per new morphing dimension; this is also illustrated in Figure 6.19 for the case of adding NPs, which will be discussed further in section 6.8.1.

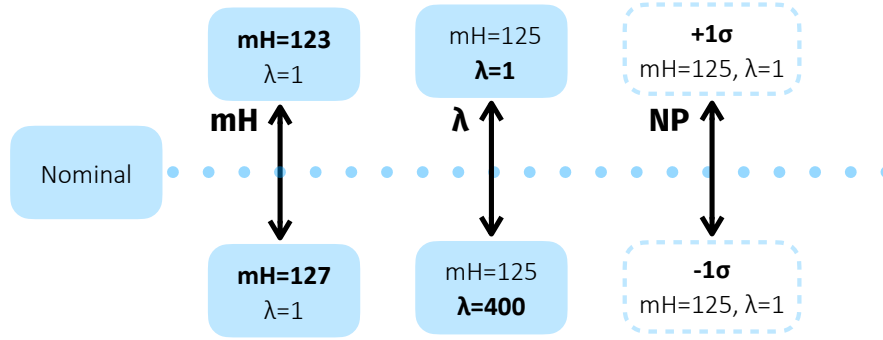


Figure 6.19: Diagram illustrating the required number of inputs for the star-morphed function to be able to obtain a continuous description of the $m_{\gamma\gamma}$ distribution in two dimensions: $m_{\gamma\gamma} \in [123 \text{ GeV}, 127 \text{ GeV}]$ and $\lambda \in [1, 400]$. The morphing function can easily be extended to more dimensions by including two additional inputs per dimension, for example to include $\pm 1\sigma$ systematic uncertainty variations (nuisance parameters, NP).

The nominal SM sample for the gg - and qg -interference contributions are shown in Figure 6.17 and Figure 6.18 respectively. All additional samples required to achieve the two dimensional morphing over m_H and λ are shown in Appendix D. As an illustrative example, Figure 6.20 displays the gg -interference distributions in category 1 for an enhanced Higgs boson width ($m_H = 125 \text{ GeV}$, $\lambda = 400$), and also a larger Higgs boson mass value ($m_H = 127 \text{ GeV}$, $\lambda = 1$). The parameter values used to described each interference distribution, obtained by fitting the model to the MC, are listed in Table 6.11 for the gg -interference, and Table 6.12 for the qg -interference contribution. The broadening of the distributions when λ increases can be seen reflected in the μ_1 and μ_2 values for the $\lambda = 1$ versus $\lambda = 400$ samples. In the case of the gg -interference, when the Higgs boson mass value was altered, all other parameters in the interference function (equation

6.18) were kept fixed to those values obtained when fitting the nominal SM sample (i.e. $m_H = 125$ GeV and $\lambda = 1$). The motivating reason in doing so was that the gg -interference morphing function seemed to be more stable in the total PDF fit, versus when all function parameters were always left free to float. This strategy of fixing all non- μ parameters, did not work for the qg -interference however, probably because the statistical fluctuations in the $m_{\gamma\gamma}$ distribution are significantly less for the qg - versus gg -interference process.

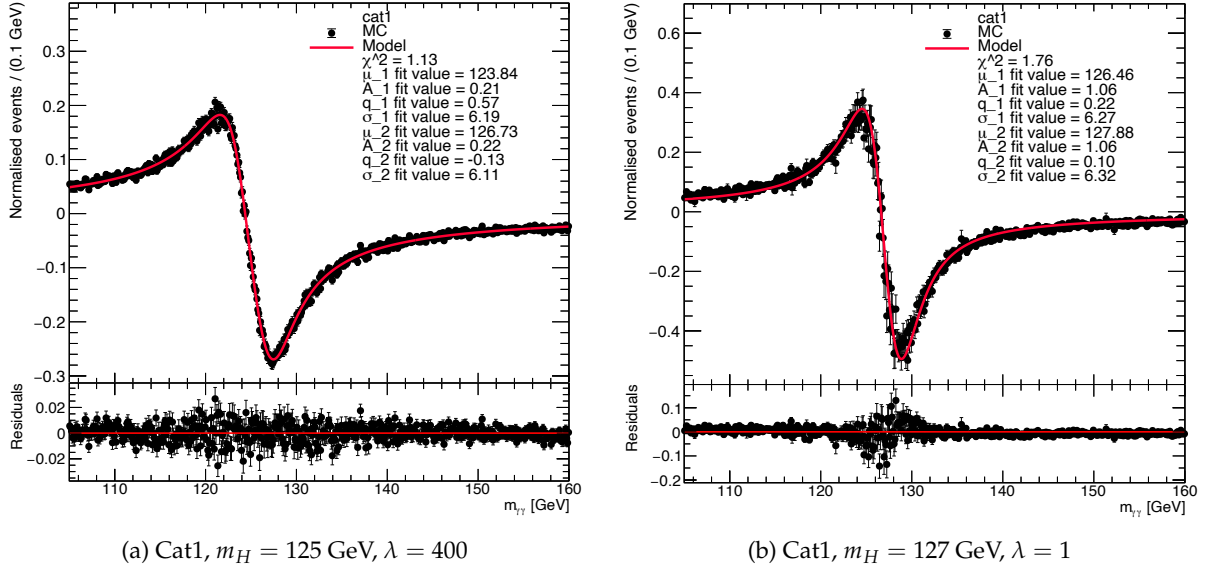


Figure 6.20: Example of the input functions required to define the gg -interference star-morphing function, in category 1. Each function is plotted on top of the corresponding MC sample, where the individual m_H and λ are listed in the individual plot captions.

Category	m_H [GeV]	λ	μ_1	A_1	q_1	σ_1	μ_2	A_2	q_2	σ_2
Cat1	125	1	124.59	1.06	0.22	6.27	125.59	1.06	0.10	6.32
Cat1	125	400	123.84	0.21	0.57	6.19	126.73	0.22	-0.13	6.11
Cat1	123	1	122.61	1.06	0.22	6.27	123.28	1.06	0.10	6.32
Cat1	127	1	126.46	1.06	0.22	6.27	127.88	1.06	0.10	6.32
Cat2	125	1	123.99	0.31	0.33	4.84	126.19	0.31	-0.04	5.32
Cat2	125	400	123.94	0.18	0.47	6.40	126.67	0.17	-0.06	6.65
Cat2	123	1	122.18	0.31	0.33	4.84	123.70	0.31	-0.04	5.32
Cat2	127	1	125.70	0.31	0.33	4.84	128.62	0.31	-0.04	5.32

Table 6.11: gg -interference function shape parameters obtained from fitting the reference MC sample with the corresponding m_H and λ values, for each analysis category.

Evaluating the star-morphed function: To study the regularity of the star-morphed function when evaluating different m_H and λ values, the morphed function was evaluated for a series of m_H and λ values. When considering alternate m_H values, the function is expected to shift

Category	m_H [GeV]	λ	μ_1	A_1	q_1	σ_1	μ_2	A_2	q_2	σ_2
Cat1	125	1	123.93	1.07	0.26	5.37	126.34	1.07	-0.14	5.00
Cat1	125	400	124.11	1.13	0.21	7.75	126.14	1.14	-0.11	7.36
Cat1	123	1	122.14	0.92	0.22	5.85	124.24	0.92	-0.07	5.43
Cat1	127	1	125.85	1.62	0.28	5.12	128.35	1.63	-0.17	4.82
Cat2	125	1	123.94	0.47	0.27	4.59	126.28	0.46	-0.19	4.43
Cat2	125	400	124.01	0.37	0.24	6.69	126.21	0.36	-0.17	6.57
Cat2	123	1	122.01	0.42	0.26	4.79	124.28	0.41	-0.16	4.55
Cat2	127	1	125.90	0.55	0.27	4.47	128.27	0.54	-0.21	4.40

Table 6.12: qg -interference function shape parameters obtained from fitting the reference MC sample with the corresponding m_H and λ values, for each analysis category.

unidirectionally along the $m_{\gamma\gamma}$ axis, and for alternate (larger) λ values instead, it is expected to cause a smearing-like effect with the two peaks move outwards away from $m_H = 125$ GeV and decrease in height, as the width parameter increases. This expected behaviour was discussed in section 6.2.3, when larger width MC samples were generated. Figure 6.21a and 6.21b display the morphed functions evaluated for alternate m_H and λ values respectively, for the qg -interference. Similar evaluation has been checked for category 2, as well as for the gg -interference in both analysis categories, and the behaviour follows that observed in Figure 6.21, as expected. The difference in normalisations for the alternate m_H value functions is due to the fact that the tails of the interference processes extend quite far in $m_{\gamma\gamma}$. Although the relative yield in the region outside $\sim m_{\gamma\gamma} \in [110 \text{ GeV}, 140 \text{ GeV}]$ is small, it is not zero as is the case for the signal process. The parametrisation of this yield variation as a function of m_H will be discussed in section 6.6.2.

Validating the star-morphed function: Validation of the morphing is done by evaluating the morphing function to an alternative m_H and λ value that is not included as a reference template, and comparing this to a MC sample produced with those values. This closure test has been done for the values $m_H = 124$ GeV and $\lambda = 100$, and these results are displayed in Figure 6.22 for the gg -interference and qg -interference for category 1. Category 2 was also evaluated and the observed result is very similar to that of category 1. The residuals between the specific interference function and the MC are shown below each plot. Whilst there are some small features in the residual distributions, this should be covered by the interference modelling uncertainty which assigns an uncertainty based on the mis-modelling between the chosen analytical function and the generated events; this uncertainty will be evaluated in section 6.8.7.

6.6.2 Parametrising the total interference yield

Since the tails of the interference distributions extend beyond the $m_{\gamma\gamma} \in [105 \text{ GeV}, 160 \text{ GeV}]$ range used in the fit, there is a slight difference in the total expected yield when changing the

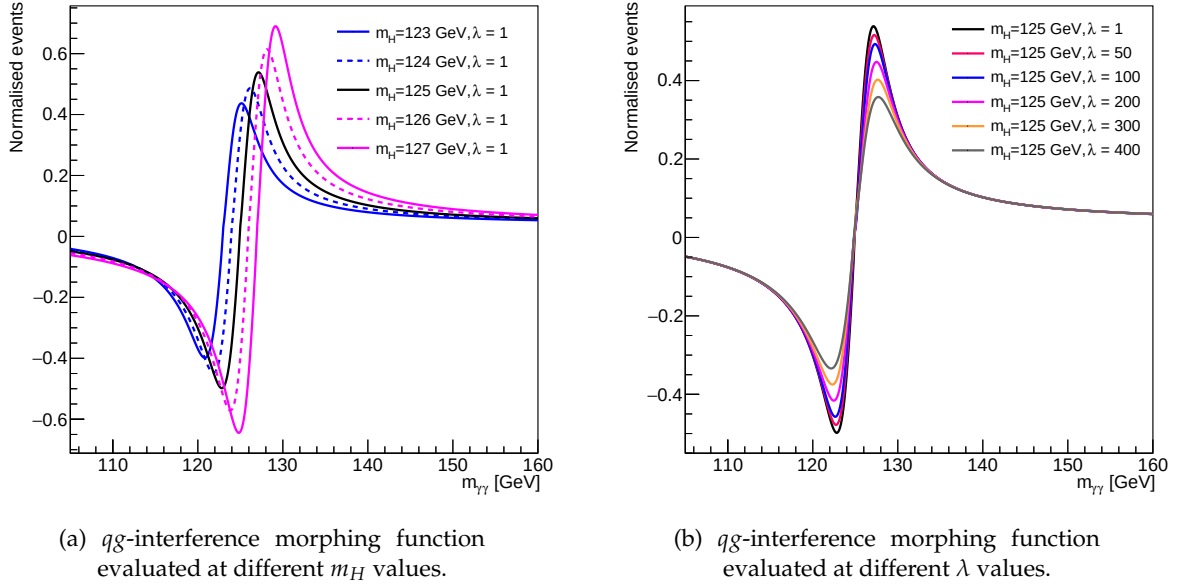


Figure 6.21: Evaluation of the qg -interference morphing function in category 1 used in the analysis. Figure 6.21a shows the function evaluated at a series of m_H values, while Figure 6.21b instead evaluates different λ values.

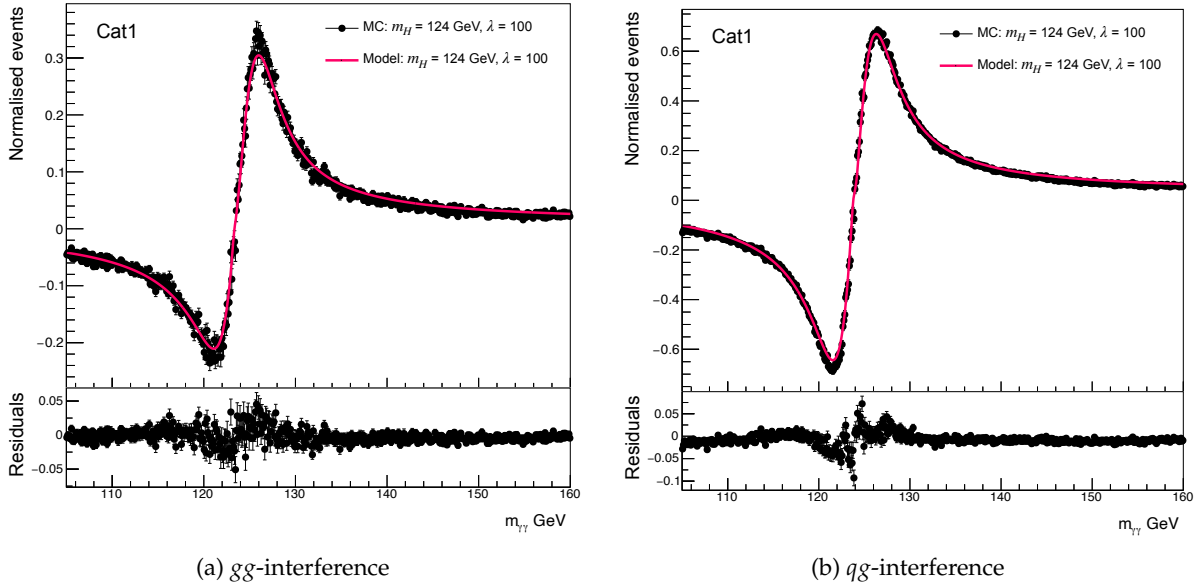


Figure 6.22: Diphoton invariant mass distribution for $m_H = 124$ GeV, $\lambda = 100$ MC sample in category 1, and the star-morphed function with the same m_H and λ values, for 6.22a gg -interference and 6.22b qg -interference.

Higgs boson mass. To account for this the interference yield is parametrised as a linear function, which is obtained via fitting the total yield values obtained for a series of m_H values. As shown in Figure 6.23 for both interference contributions in category 1. In each case, the yield values for each value of m_H are indicated by the black points, where the m_H value is calculated as the

relative difference with the SM value $m_H^{\text{SM}} = 125$ GeV. The linear function is defined as:

$$\text{yield} = \alpha \times (m_H - m_H^{\text{SM}}) + \beta. \quad (6.22)$$

Similar plots were also made for both interference processes in category 2, and similar behaviour was seen. Table 6.13 summarises the fitted α and β values obtained for each interference process, for each analysis category.

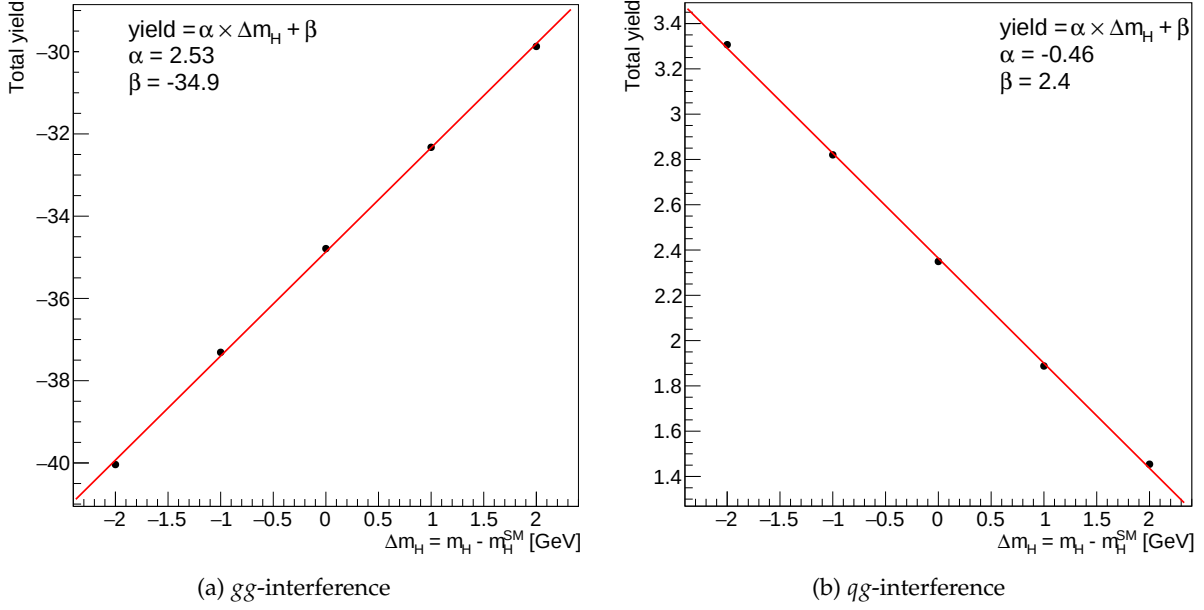


Figure 6.23: Interference yields in category 1, parametrised as a function of the difference between the alternate m_H value and the SM Higgs mass $m_H^{\text{SM}} = 125$ GeV.

Process	Category	α	β
gg -interference	Cat1	2.53	-34.9
gg -interference	Cat2	1.83	-36.2
qg -interference	Cat1	-0.46	2.4
qg -interference	Cat2	-0.55	6.5

Table 6.13: Parameters defining a linear function, as per equation 6.22, obtained by fitting the distribution of interference yield values as a function of $\Delta m_H = m_H - m_H^{\text{SM}}$.

6.7 Background model

The main background processes present in the $m_{\gamma\gamma}$ distribution near the resonant signal peak is from non-resonant processes with $\gamma\gamma$, $\gamma + j$ or jj final states. The dominant and irreducible background comes from SM QCD diphoton production (see the Feynman diagram in Figure 3.7), and accounts for roughly 80% of the total background contributions. Events where jets are present in

the final state can pass the event selection as outlined in section 6.3.2, where photons are produced inside a jet by neutral meson decay, and consequently one or two jets are mistakenly identified as a photon. Drell-Yan events where both final state electrons are mis-identified as photons make up only a very small fraction ($< 1\%$) of the total background.

The background $m_{\gamma\gamma}$ shape is modelled by one of five candidate functions, $\mathcal{B}(m_{\gamma\gamma})$, for each analysis category separately, where the parameters of this analytical function are fitted to data. The five functions considered are :

- Exponential Function (Exp):

$$f(m_{\gamma\gamma}) = e^{p_0 \cdot m_{\gamma\gamma}}, \quad (6.23)$$

- Exponential Function of 2nd Order Polynomial (ExpPoly2):

$$f(m_{\gamma\gamma}) = e^{p_0 \cdot m_{\gamma\gamma}^2 + p_1 \cdot m_{\gamma\gamma}}, \quad (6.24)$$

- Exponential Function of 3rd Order Polynomial (ExpPoly3):

$$f(m_{\gamma\gamma}) = e^{p_0 \cdot m_{\gamma\gamma}^3 + p_1 \cdot m_{\gamma\gamma}^2 + p_2 \cdot m_{\gamma\gamma}}, \quad (6.25)$$

- Bernstein polynomial of order N :

$$B_N(m_{\gamma\gamma}) = \sum_{i=0}^N p_i \cdot b_{i,N} \text{ with } b_{i,N} = \binom{N}{i} m_{\gamma\gamma}^i (1 - m_{\gamma\gamma})^{N-i}, \quad (6.26)$$

- First-Order Power Law Function:

$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{p_0}. \quad (6.27)$$

Each of these PDFs are additionally multiplied by a normalisation factor N , which corresponds to the total expected yield from the background process. The analytical function chosen in each category is based on the results of the *spurious signal* test, which will be described in section 6.7.1, along with the results and selected functions $\mathcal{B}(m_{\gamma\gamma})$ to be used to model the background in each analysis category.

6.7.1 Spurious signal test and background function results

Generally speaking, *spurious signal* is defined as an excess of events in the background-only $m_{\gamma\gamma}$ distribution which can mimic the signal shape specifically in the signal region where we expect an excess of events to appear due to the presence of the Higgs boson. The spurious signal test is

used as a measure to quantify which function should be used to model the background in each analysis category. This is because the amount of spurious signal, S_{sp} quantifies the amount of bias associated with a given choice of function, $\mathcal{B}(m_{\gamma\gamma})$. This test is performed by constructing a signal plus background model, and fitting this to the background-only template (constructed using MC simulated events for the background processes). This is repeated for each of the five functions listed above, as well as for each category. In each case, the bias S_{sp} is measured, and the χ^2 of the fit is also noted. The background templates used are displayed in Figure 6.24 for each of the event categories. Each fit is performed across the nominal $\gamma\gamma$ mass range of $105 < m_{\gamma\gamma} < 160$

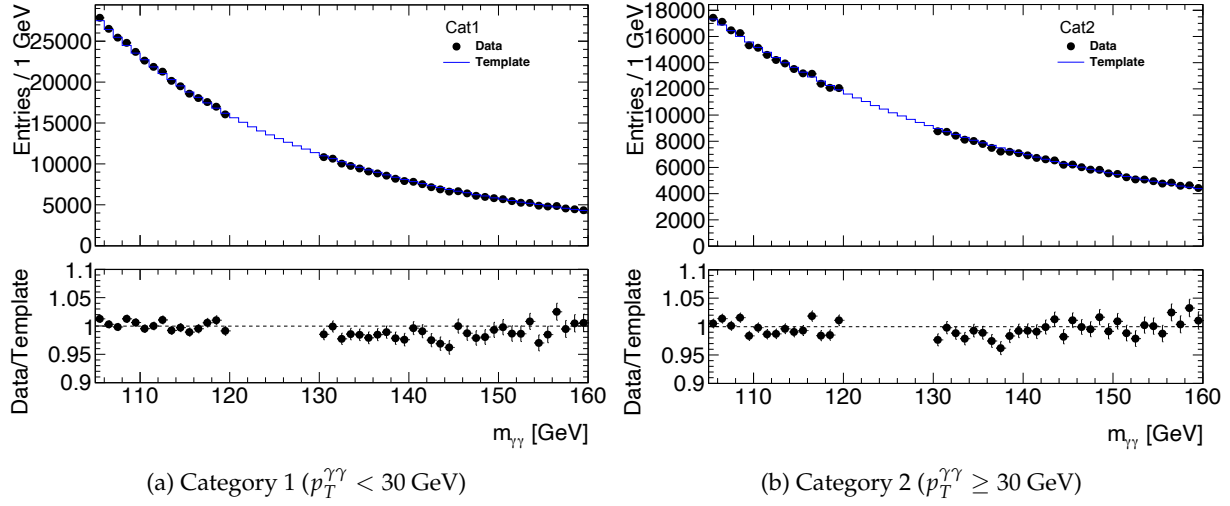


Figure 6.24: Background $m_{\gamma\gamma}$ template distributions (shown in blue), for 6.24a category 1, and 6.24b category 2. Data in the sideband regions ($105 < m_{\gamma\gamma} < 120$ GeV or $130 < m_{\gamma\gamma} < 160$ GeV) is also displayed.

GeV. The fitted number of signal events is computed in intervals of 0.5 GeV across the mass range $123 \leq m_{\gamma\gamma} \leq 127$ GeV where negative fluctuations are also accounted for. The number of spurious signal events, N_{sp} , is then defined by the maximum of fitted number of signal events within this range. A candidate function is deemed to have passed the test if at least one of the following two criteria are satisfied:

- $N_{sp} < 10\% \cdot N_{sp,exp}$
where $N_{sp,exp}$ is the expected number of signal events in that category;
- $N_{sp} < 20\% \cdot \sigma_{sig}$
where σ_{sig} is the statistical uncertainty on the expected number of signal events (which are due to statistical fluctuations in the background).

In addition, the fit must result in a reduced χ^2 probability of 1% at least. This is to ensure the full $m_{\gamma\gamma}$ range is well described, as it specifically prevents against the case where there is a low N_{sp} in the range $121 < m_{\gamma\gamma} < 129$ GeV for example, but the sideband regions do not have a good fit quality. If more than one function satisfies these criteria, the one with the smallest number of degrees

of freedom (ndof) is selected. Out of the functions which passed the spurious signal test, the one with the least number of degrees of freedom is chosen for $\mathcal{B}(m_{\gamma\gamma})$. If the functions all have the same number of degrees of freedom, the one with the lowest value of N_{sp} is selected. The results of the spurious signal test performed for this analysis are presented in Table 6.14 (Table 6.14a for category 1, and Table 6.14b for category 2); only the results for the functions which passed the test are shown. Since there are two functions in both categories which passed, ExpPoly2 was chosen in both categories since it has the least number of degrees of freedom. The value of the spurious signal N_{sp} in each event category is included as a systematic yield uncertainty on the signal due to the background modelling; see section 6.9 for more details.

Function	N_{sp}/σ_{sig}	$N_{sp}/N_{sp,exp}$	N_{sp}	ndof	χ^2/ndof	$p(\chi^2)[\%]$	Result
ExpPoly2	-52.8	-8.7	-190	2	1.2	17.7	PASS ← Selected
ExpPoly3	-54.5	-8.7	-189	3	1.2	15.4	PASS

(a) Category 1 results

Function	N_{sp}/σ_{sig}	$N_{sp}/N_{sp,exp}$	N_{sp}	ndof	χ^2/ndof	$p(\chi^2)[\%]$	Result
ExpPoly2	-31.1	-5.2	-94	2	0.9	68.3	PASS ← Selected
ExpPoly3	-31.6	-5.2	-94	3	0.9	64.7	PASS

(b) Category 2 results

Table 6.14: Spurious signal test results. In both analysis categories, the ExpPoly2 function was chosen for $\mathcal{B}(m_{\gamma\gamma})$ since it has the least number of degrees of freedom amongst the functions which passed.

Following the selection of the function $\mathcal{B}(m_{\gamma\gamma})$, the parameters defining the shape and yield per category are obtained by fitting this function to the data in two sideband regions (also known as control regions), defined by $105 < m_{\gamma\gamma} < 120$ GeV and $130 < m_{\gamma\gamma} < 160$ GeV, either side of the signal region ($m_{\gamma\gamma} \in [120, 130]$ GeV) which remains blinded. Figure 6.25 displays fitting $\mathcal{B}(m_{\gamma\gamma})$ to the data in the sideband regions for the two categories. Table 6.15 lists the fitted shape and yield parameters obtained.

Category	Function	p_0	p_1	N_{bkg}
Cat1	ExpPoly2	-4.15	1.10	664,058.1
Cat2	ExpPoly2	-2.96	0.67	510,157.1

Table 6.15: Background shape and yield parameters obtained by fitting $\mathcal{B}(m_{\gamma\gamma})$ to data in the sideband regions of the $m_{\gamma\gamma}$ distribution, in each category. The two shape (p_0 and p_1) parameters define the selected ExpPoly2 function, as per equation 6.7, and extracted from the fit to data.

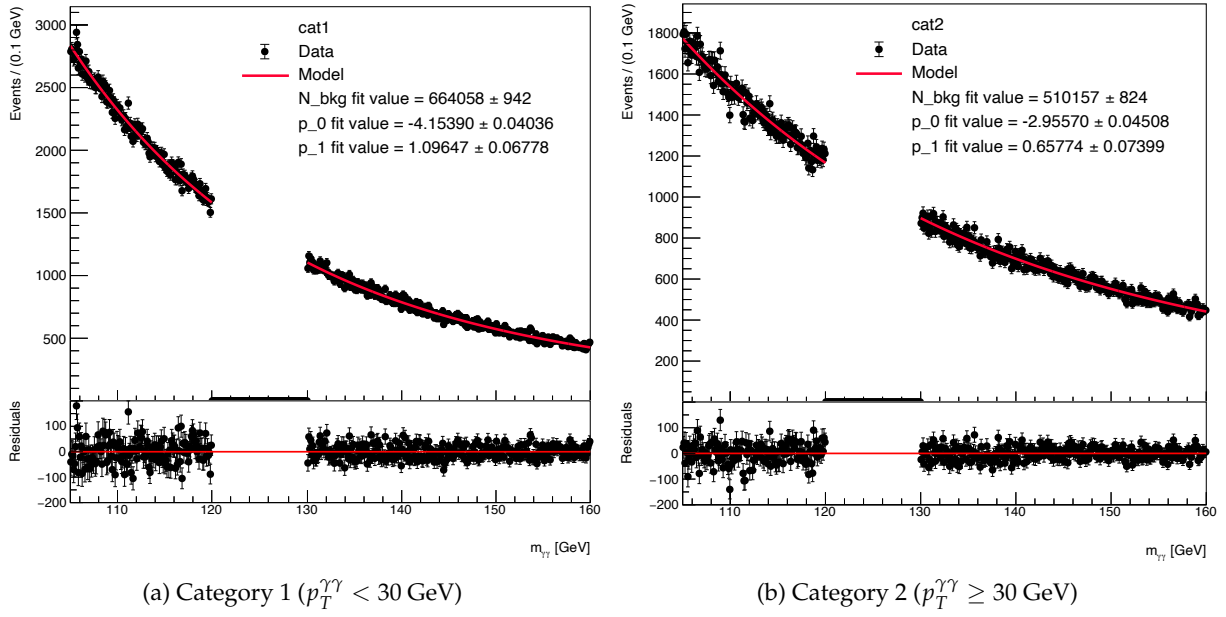


Figure 6.25: Diphoton invariant mass distribution corresponding to data in the sideband regions (black), which is fitted with the background function, $\mathcal{B}(m_{\gamma\gamma}) = \text{ExpPoly2}$ (red line), for category 1 (Figure 6.25a) and category 2 (Figure 6.25b). The values of the fitted background shape (p_0 and p_1) and yield (N_{bkg}) parameters are displayed. The region within $m_{\gamma\gamma} \in [120, 130]$ GeV is blinded since it is the signal region.

6.8 Systematic uncertainties

This section details the treatment of all systematic uncertainties that impact the target $H \rightarrow \gamma\gamma$ measurement, and how they're accounted for in the likelihood fit. Systematic uncertainties on the measurement are generally grouped into either experimental or theoretical uncertainties and can relate to any one or all of the signal, interference, and background processes present. Inefficiencies in the performance of the ATLAS detector are quantified and accounted for through experimental uncertainties, which relate to the reconstruction, identification and calibration of the measured particles. Theoretical uncertainties instead arise for example due to assumptions or choices made in the MC generation procedure, cross-section calculations, and uncertainties associated with the specific analytic function used to model each of the signal, interference and background contributions.

Systematic uncertainties are accounted for in the likelihood model by means of *nuisance parameters* (NP), θ , which are allowed to float in the fit such that their value is the one that best describes the observed dataset. These uncertainties are included by multiplying the relevant NP θ , by one of

the following *response functions*:

$$F_G(\delta, \theta) = (1 + \delta\theta) \quad \text{Gaussian constraint} \quad (6.28)$$

$$F_{LN}(\delta, \theta) = e^{\sqrt{\ln(1+\delta^2)}\theta} \quad \text{Log-normal constraint} \quad (6.29)$$

$$F_{AS}(\delta^\pm, \theta) = \begin{cases} P_6(\theta; \delta^-, 0, \delta^+), & \text{if } \theta \in [\delta^-, \delta^+] \\ \exp(\theta), & \text{outside} \end{cases} \quad \text{Asymmetric constraint,} \quad (6.30)$$

where δ is the evaluated size of the uncertainty (in the case of asymmetric variations the $\pm 1\sigma$ NP variations may have different values, $\delta^\pm$), $P_6(\theta; \delta^-, 0, \delta^+)$ is a degree six polynomial which is constrained to pass through the points $\delta^-, 0, \delta^+$; $\exp(\theta)$ is the exponential extrapolation either side of the polynomial, P_6 [118]. A log-normal constraint would be used for a systematic uncertainty with a non-physical negative variation, for example the uncertainty on the luminosity. Uncertainties that affect multiple processes are described by correlated nuisance parameters, where the same nuisance parameter θ is used to describe all relevant impacts, but δ can take on different values. This section will describe the procedure used to compute the uncertainty amplitude δ for each NP θ , for the signal and interference processes such that they can be included in the likelihood model, described in section 6.9.

Both experimental and theoretical systematic uncertainties can impact either the shape of the kinematic distribution(s) of interest and/or the overall normalisation of the distribution(s); the procedure used to evaluate them varies according to their impact. Shape effects are generally evaluated by computing the $\pm 1\sigma$ variation on the nominal distribution using MC simulated events. The effect on the overall normalisation is instead computed using MC events by taking the relative difference between the nominal expected number of events, with the yield of the $\pm 1\sigma$ variation. Since the effect can be different in each analysis category, the impact is evaluated separately as:

$$\delta N_c^{\pm 1\sigma} = \frac{N_c^{\pm 1\sigma}}{N_c^{\text{nom.}}} - 1, \quad (6.31)$$

where c denotes the specific analysis category considered.

The experimental systematic uncertainties will be described in section 6.8.1, while the remaining sections present the theoretical systematics. Theoretical uncertainties derived from the incomplete understanding of the various theoretical parameters used in the analysis. This includes for example the uncertainty on the cross-section of the diphoton decay channel, uncertainties associated with the MC generation procedure used to obtain the simulated events, as well as the imperfect calculation of other SM parameters which may be included in the analysis and affect the final measurement of the Higgs boson width. Section 6.8.2 describes the uncertainties associated with the cross-section and luminosity which affect only the overall normalisation of $m_{\gamma\gamma}$. The theoretical uncertainties deriving from the QCD scale and choice of parton density functions

(PDFs) are outlined in section 6.8.3. Section 6.8.4 describes the uncertainty associated with the cross-section scaling factor applied to the gg -interference process. Uncertainties associated with the MC generation procedure are discussed in sections 6.8.5 and 6.8.6. The specific choice of functional form used to model the individual signal, interference, and background components also carry a source of theoretical uncertainty, usually referred to as a modelling uncertainty. The impact of these choices on the analysis sensitivity to the parameter of interest, for each of these processes, is presented in section 6.8.7.

6.8.1 Experimental uncertainties

Experimental uncertainties can alter both the shape and overall normalisation of the $m_{\gamma\gamma}$ distribution, and therefore impact the sensitivity of our measurement of the Higgs boson width POI, λ . In $H \rightarrow \gamma\gamma$ analyses, experimental uncertainties derive from efficiencies associated with the photon identification, isolation, trigger, and photon energy calibration. All of the experimental uncertainties are evaluated using MC simulated signal and interference samples. In general since the background is modelling by fitting the chosen analytical function to data, there are no additional systematic uncertainties associated with the background aside from the those due to the choice of analytical function used, i.e. spurious signal and modelling bias uncertainty.

The full set of experimental systematics associated with the photon energy calibration consists of 70 energy scale NPs, and 9 energy resolution NPs. These uncertainties derive from detector effects which can each cause variations in the peak position (mean) and resolution of the $m_{\gamma\gamma}$ distribution, for example due to material effects (specifically the cryostat material, calorimeter material and the pre-sampler material), inter-layer calibration, efficiency factors, and photon fake rates. For simplicity in this analysis (to ensure fit stability, and given it is the first analysis using $\gamma\gamma$ interference), the full NP model is simplified into one NP parameterising the photon energy scale (PES), and one parameterising the photon energy resolution (PER). The PES and PER variations affect both the signal and interference shape, and the yield, in each analysis category. The shape effects due to both the PES and PER are expected to impact the sensitivity of the analysis, given the PES influences the peak position of the $m_{\gamma\gamma}$ distribution, while the PER results in an uncertainty on the width of the $m_{\gamma\gamma}$ distribution. The PES and PER shape variations are modelled and evaluated using MC simulated events of the $\pm 1\sigma$ variations of the $m_{\gamma\gamma}$ distribution for the signal and interference contributions separately; these will be outlined below.

Signal variations due to the photon energy calibration

The effect on the signal due to the uncertainties associated with the photon energy scale and energy resolution affect both the shape and the yield. These effects are included in the fit to data through response functions that affect the mean, μ_{CB} , and resolution, σ_{CB} , of the DSCB function used to model the signal. Since the impact of the PES and PER systematic uncertainties directly

corresponds to an impact on the μ_{CB} and σ_{CB} parameters respectively, the other four parameters of the DSCB are considered to be not affected. The $\delta^\pm$ variations are evaluated per category, for each of the PES and PER systematics, and are each computed using the MC signal samples with $\lambda = 1$.

For the PES, the *ratio-of-mean* technique is used: the mean of $m_{\gamma\gamma}$ distributions are computed for the nominal and $\pm 1\sigma$ varied distributions. The PES uncertainty amplitude $\delta_{\text{PES}}^\pm$ is then evaluated as:

$$\delta_{\text{PES}}^\pm = \frac{\langle m_{\gamma\gamma}^{\pm 1\sigma} \rangle}{\langle m_{\gamma\gamma}^{\text{nom}} \rangle} - 1. \quad (6.32)$$

Figure 6.26a displays the nominal $m_{\gamma\gamma}$ distribution, and $\pm 1\sigma$ variations for the signal process, for category 1 defined in the analysis. The computed $\delta_{\text{PES}}^\pm$ value is included in the plot legend. The distributions for category 2 also looks similar, and are displayed in Figure E.1 of Appendix E. The uncertainty amplitude evaluates to $\pm 0.41\%$ in category 1, and $\pm 0.45\%$ in category 2. This can be seen visually in the distributions shown in Figure 6.26b whereby the distribution corresponding to the -1σ PES variation is shifted by 0.36 GeV towards lower values of $m_{\gamma\gamma}$ with respect to the mean value of 124.99 GeV for the nominal distribution, and the $+1\sigma$ PES variation instead is shifted by the same amount towards higher values of $m_{\gamma\gamma}$. Scale uncertainties are implemented in the fit to data with a Gaussian constraint response function using the $+1\sigma$ variation, because of the high symmetry observed. The constraint is applied to μ_{CB} as:

$$\mu'_{\text{CB}} = (\mu_{\text{CB}} + m_H - m_H^{\text{SM}}) F_{\text{PES}}(\delta^\pm, \theta), \quad (6.33)$$

where the response function is of the type $F_{\text{PES}}(\delta^\pm, \theta) = (1 + \delta_{\text{PES}}^\pm \cdot \theta_{\text{PES}})$.

For the PER, the *ratio of inter-quartile* values computed for the $m_{\gamma\gamma}$ distribution is used: the inter-quartile is computed as $S = \text{CDF}^{-1}(75\%) - \text{CDF}^{-1}(25\%)$, where CDF is the cumulative distribution function of the $m_{\gamma\gamma}$ nominal distribution and for the distributions where the resolution is varied by $\pm 1\sigma$. The PER uncertainty amplitude, $\delta_{\text{PER}}^\pm$, is then evaluated as:

$$\delta_{\text{PER}}^\pm = \frac{S^{\pm 1\sigma}}{S^{\text{nom}}} - 1. \quad (6.34)$$

Figure 6.26b shows the $\pm 1\sigma$ PER variations about the nominal $m_{\gamma\gamma}$ distribution in category 1 of the analysis. The computed values of $\delta_{\text{PER}}^\pm$ range between 4% for category 1, up to 6% for category 2. The effect on the $m_{\gamma\gamma}$ distribution due to the PER variations is evident in Figure 6.26b whereby the resolution of the distribution increases (decreases) to 2.3 GeV (2.1 GeV) for the $+1\sigma$ (-1σ) variation, with respect to the nominal value of 2.2 GeV. Resolution uncertainties are implemented in the fit using an asymmetric constraint (equation 6.30) response function, to take into account

differences in the $\pm 1\sigma$ variations. The constraint is applied to σ_{CB} as:

$$\sigma'_{\text{CB}} = \sigma_{\text{CB}} F_{\text{PER}}(\delta^{\pm}, \theta) \quad (6.35)$$

where the response function $F_{\text{PER}}(\delta^{\pm}, \theta)$ is a linear interpolation of θ_{PER} between $(1 + \delta_{\text{PER}}^{-})$ and $(1 + \delta_{\text{PER}}^{+})$. Table 6.16 lists the computed uncertainty amplitude values for the signal PES and PER

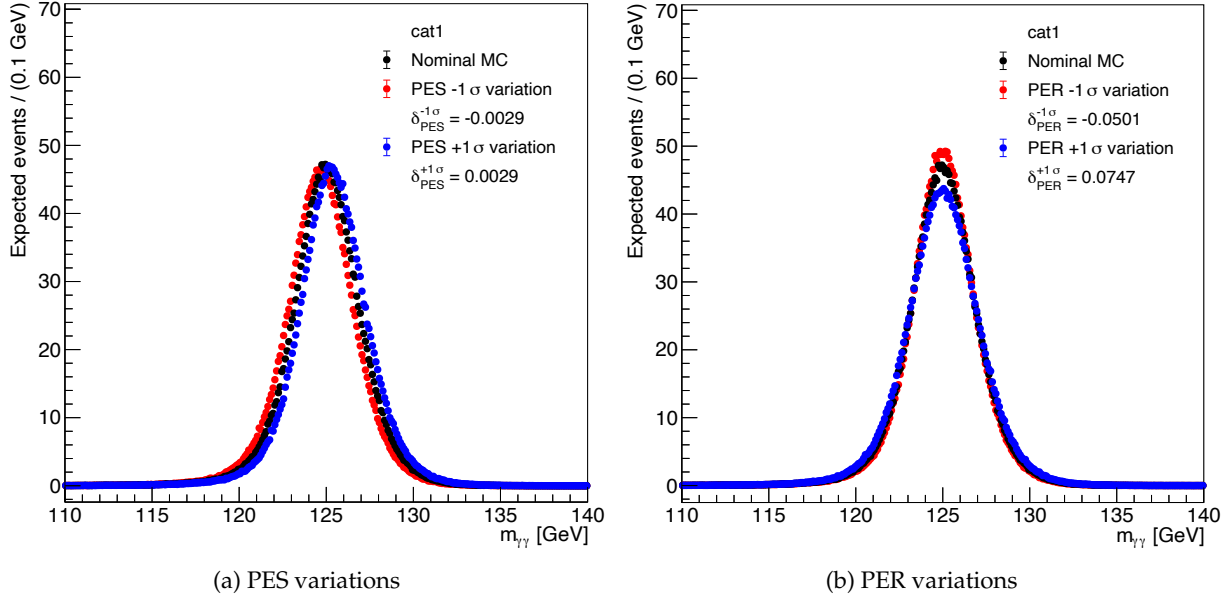


Figure 6.26: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (6.26a) photon energy scale and (6.26b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the signal process in category 1 ($p_T^{\gamma\gamma} < 30$ GeV).

systematic uncertainties in each of the two event categories.

Category	δ_{PES}^{-}	δ_{PES}^{+}	δ_{PER}^{-}	δ_{PER}^{+}
Cat1	-0.3%	+0.3%	-7.5%	+7.5%
Cat2	-0.3%	+0.3%	-9.6%	+9.6%

Table 6.16: Uncertainty amplitude values computed for the $\pm 1\sigma$ photon energy scale and resolution variations, per event category, for the signal process.

Interference variations due to the photon energy calibration

Similarly to the signal, the systematic uncertainties on the PES and PER impact both the shape and yield of the $m_{\gamma\gamma}$ distributions for the two contributing interference processes. The shape effects due to these systematic variations are parametrised by extending the two-dimensional star-morphing, as described in section 6.6.1, to four dimensions corresponding to the following four parameters: m_H , λ , plus one additional dimension for each of the PES and PER. This requires an additional two reference input functions for each additional degree of morphing to be

included in the updated star-morphed function. Although it is relatively trivial to produce the necessary input functions for the full NP scheme (i.e. 70 PES variations plus 9 PER variations), this significantly impacts the fit stability, and hence further motivation to proceed only with the simplified scheme of having one combined systematic for each of the PES and PER. The gg - and qg -interference contributions are treated independently since the $m_{\gamma\gamma}$ distributions have different shapes for each interference process and hence there is one star-morphing function defined for each contribution.

Figure 6.27a (Figure 6.27b) show the PES (PER) $\pm 1\sigma$ systematic variations on the nominal gg -interference $m_{\gamma\gamma}$ distribution, while Figure 6.28a (Figure 6.28b) displays the respective PES (PER) variations for the qg -interference process in category 1 of the analysis. Similar distributions evaluated in category 2 are shown in Appendix E.1. As was observed for the signal, the effect of the $\pm 1\sigma$ PES variation causes the $m_{\gamma\gamma}$ distribution of the gg -interference to shift by around 0.3 GeV towards either lower or higher $m_{\gamma\gamma}$ values respectively. The PER variations instead cause a broadening ($+1\sigma$) or narrowing (-1σ) of the distribution with respect to the nominal.

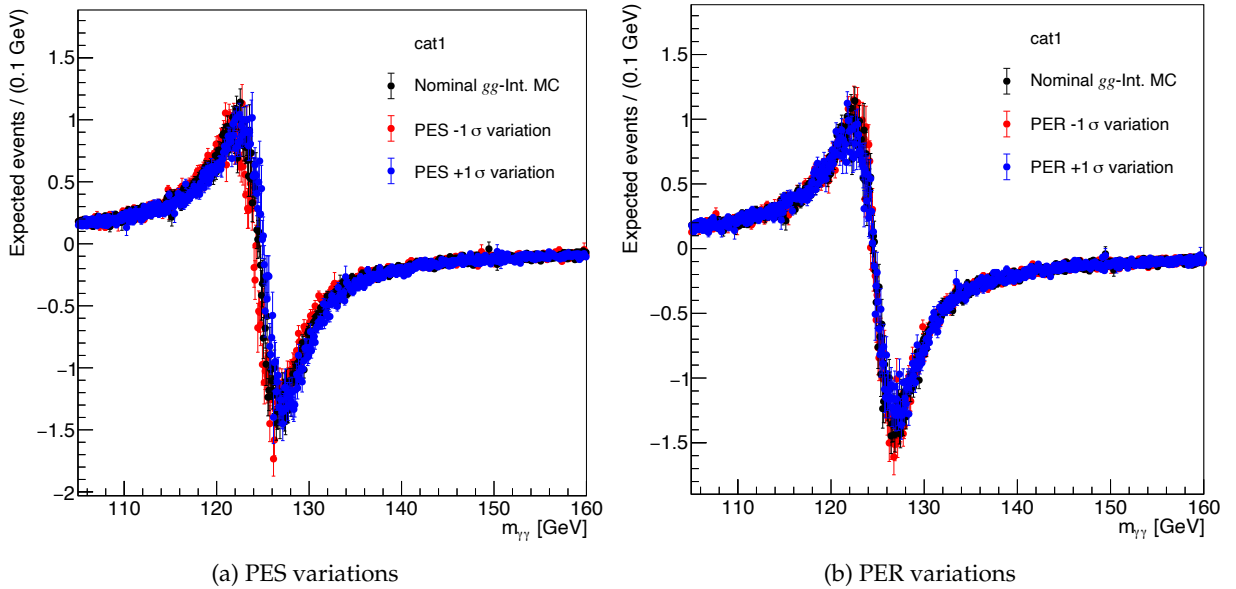


Figure 6.27: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (6.27a) photon energy scale and (6.27b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the gg -interference process in category 1 ($p_T^{\gamma\gamma} < 30$ GeV).

Each of these systematic variations are then fitted with the analytical function chosen to parametrise the interference lineshapes, as per equation 6.18 in section 6.6. These distributions, and the analytical functions describing them are displayed in Appendix E.2: Figure E.4 and E.5 display the gg -interference $\pm 1\sigma$ PES and PER variations for category 1 and 2 respectively, while Figure E.6 and E.7 display the same for the qg -interference variations. In each case the function parameters obtained from fitting the $m_{\gamma\gamma}$ MC distributions are displayed in the upper right corner of each

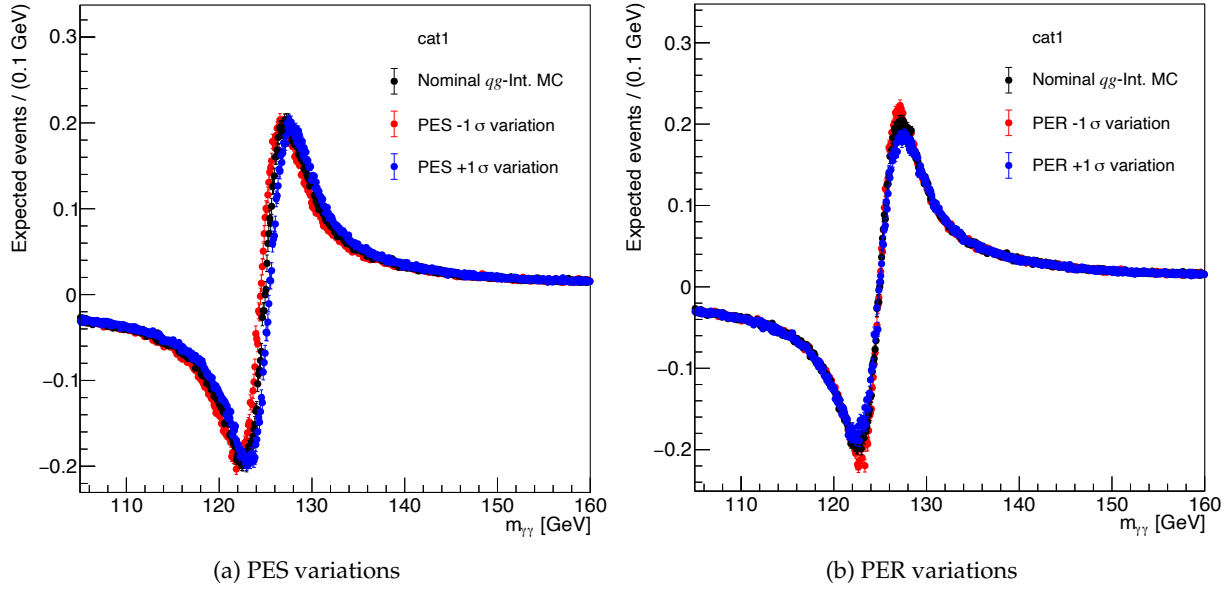


Figure 6.28: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (6.28a) photon energy scale and (6.28b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the qg -interference process in category 1 ($p_T^{\gamma\gamma} < 30$ GeV).

plot, along with the χ^2 goodness of fit value.

The four-dimensional star-morphing function is then defined including the PES and PER systematic shape variations, for each interference contribution. Figure 6.29 and Figure 6.30 displays the resulting star-morphed function evaluated at a series of systematic variation values for the gg - and qg -interference respectively. Note that the star-morphed function is also able to be evaluated beyond the defined input reference values; this is shown by the $\pm 2\sigma$ variations for each shape systematic.

Yield uncertainties

Yield uncertainties act on the overall number of expected events of a given analysis category at reconstruction level, whereby events can migrate among categories or affect the diphoton selection efficiency. The leading sources of experimental yield systematics derive from: the efficiency of the photon *trigger* ('PH_EFF_TRIGGER'), the photon *identification* efficiency ('PH_EFF_ID'), and the modelling of *pileup* in MC simulated events ('PRW_DATASF'). The PER and PES shape systematics also have an impact on the category yield, which are correlated with the shape NPs. The values for each category c are computed as per equation 6.31, as the relative difference between $\pm 1\sigma$ varied yields and the nominal one obtained using MC simulated events. Each source of systematic uncertainty is treated as fully correlated among the categories. The $\pm 1\sigma$ variations for each of these yield systematics are displayed in Table 6.17 for the signal process, Table 6.18 for gg -interference and Table 6.19 for qg -interference.

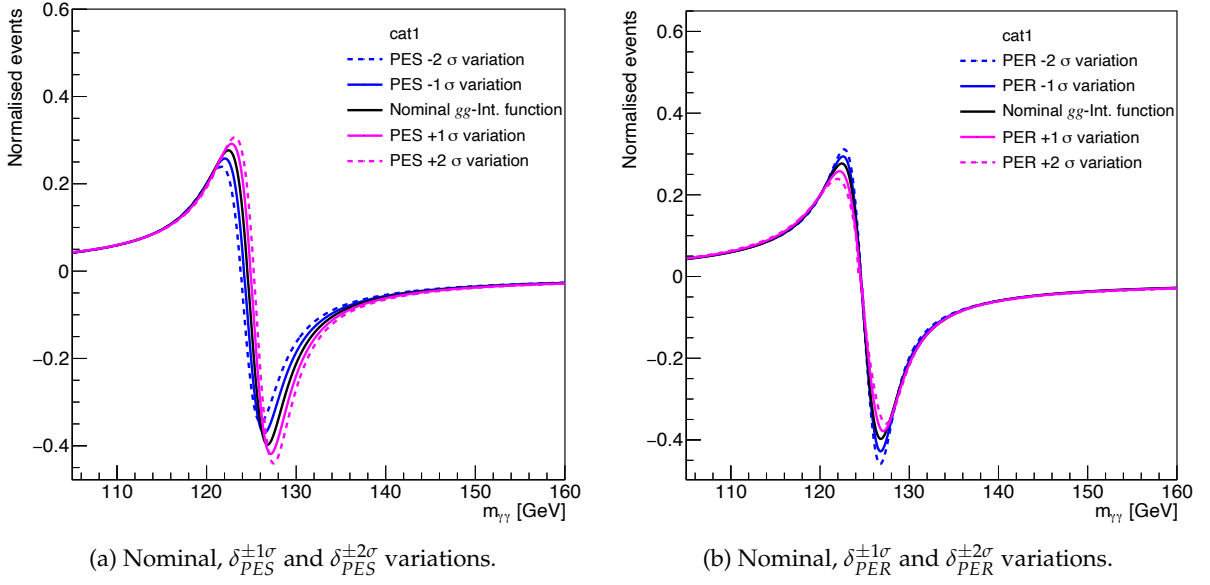


Figure 6.29: Diphoton invariant mass distributions for the star-morphed gg -interference functions evaluated at the nominal value, as well as four systematic variations for the PES systematic (6.29a), and the PER systematic (6.29b).

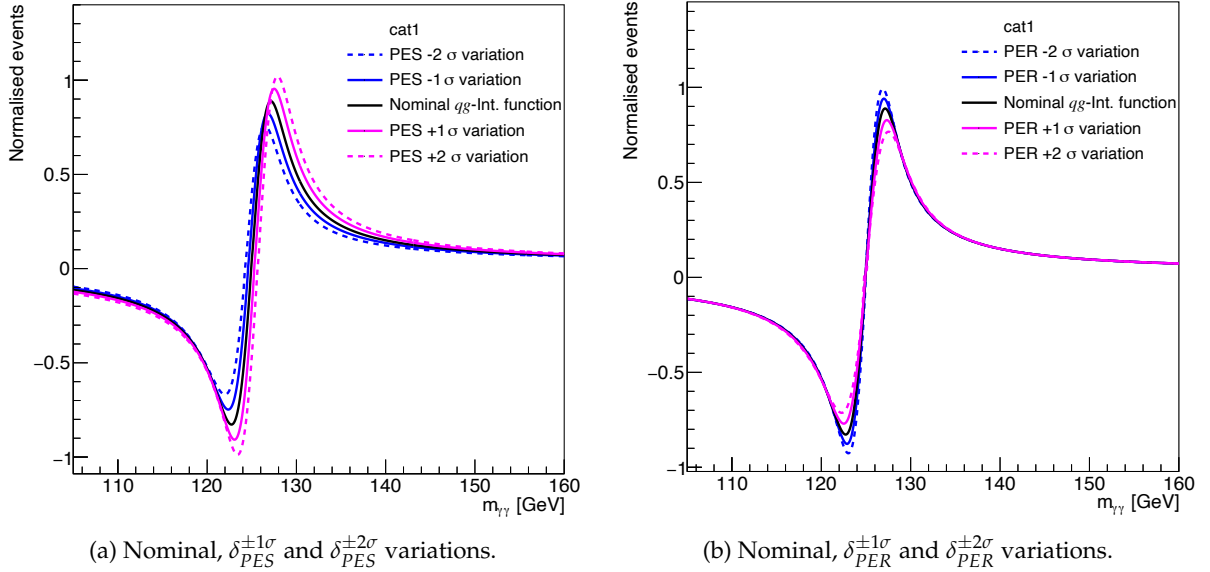


Figure 6.30: Diphoton invariant mass distributions for the star-morphed qg -interference functions evaluated at the nominal value, as well as four systematic variations for the PES systematic (6.30a), and the PER systematic (6.30b) in category 1 ($p_T^{\gamma\gamma} < 30$ GeV).

6.8.2 Cross-section and luminosity

The total integrated luminosity recorded by ATLAS during the Run 2 data-taking period is calculated to have a central value of 140.1 fb^{-1} , with an uncertainty of 0.86% [101] which is included in the statistical model as a global yield uncertainty.

Category	PES		PER		PRW_DATASF		PH_EFF_ID		PH_EFF_TRIGGER	
	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$
Cat1 ($c = 1$)	0.05	-0.05	-0.01	0.01	-0.69	0.69	1.82	-1.82	0.95	-0.95
Cat2 ($c = 2$)	0.04	-0.04	-0.01	0.01	-0.63	0.63	1.76	-1.76	0.97	-0.97

Table 6.17: Expected percentage impact of various photon-related systematic uncertainties on the number of selected diphoton events (in simulation) on the resonant signal process, $\delta N_c^{\pm 1\sigma}$, per event category.

Category	PES		PER		PRW_DATASF		PH_EFF_ID		PH_EFF_TRIGGER	
	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$
Cat1 ($c = 1$)	-2.70	2.70	0.26	-0.26	-1.05	1.05	1.34	-1.34	1.05	-1.05
Cat2 ($c = 2$)	-2.03	2.03	0.28	-0.28	-0.66	0.66	1.55	-1.55	1.03	-1.03

Table 6.18: Expected percentage impact of various photon-related systematic uncertainties on the number of selected diphoton events (in simulation) on the gg -interference process, $\delta N_c^{\pm 1\sigma}$, per event category.

Category	PES		PER		PRW_DATASF		PH_EFF_ID		PH_EFF_TRIGGER	
	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$	-1σ	$+1\sigma$
Cat1 ($c = 1$)	-7.63	7.63	0.40	-0.40	-1.53	1.53	0.33	-0.33	1.35	-1.35
Cat2 ($c = 2$)	-3.93	3.93	0.09	-0.09	-0.44	0.44	1.34	-1.34	1.12	-1.12

Table 6.19: Expected percentage impact of various photon-related systematic uncertainties on the number of selected diphoton events (in simulation) on the qg -interference process, $\delta N_c^{\pm 1\sigma}$, per event category.

The degree of accuracy with which are able to compute the expected number of diphoton events produced in the diphoton decay channel is limited by the precision of the $H \rightarrow \gamma\gamma$ branching ratio, the higher-order terms which are missing in the perturbative QCD calculations, as well as the accuracy of the chosen parton density functions. The latter two sources of theoretical uncertainties will be discussed in section 6.8.3. The $H \rightarrow \gamma\gamma$ branching ratio (0.002) has an asymmetric uncertainty of $^{+2.90\%}_{-2.84\%}$ [3]. This is included in the statistical model as an overall normalisation uncertainty (since it does not alter the shape of the $m_{\gamma\gamma}$ distribution).

6.8.3 Scale and PDF uncertainties

The absence of higher-order terms in the perturbative QCD calculations affects the precision with which we can calculate the expected number of diphoton events. The magnitude of such uncertainties, commonly referred to as QCD *scale* uncertainties, are typically evaluated for a specific process by varying the renormalisation and factorisation scales which are used at the generator level. Additional samples are generated where the renormalisation scale (μ_R) and the factorisation scale (μ_F) are correlated and vary between half and double the nominal values, meaning the following sets of samples are produced: ($\mu_R = 0.5, \mu_F = 0.5$), ($\mu_R = 0.5, \mu_F = 1.0$), ($\mu_R = 1.0$,

$\mu_F = 0.5$), $(\mu_R = 2.0, \mu_F = 1.0)$, $(\mu_R = 1.0, \mu_F = 2.0)$, $(\mu_R = 2.0, \mu_F = 2.0)$, for each of the signal gg - and qg -interference processes. The overall scale uncertainty is then calculated as the relative difference across the $m_{\gamma\gamma}$ distribution with respect to the nominal sample. The envelope of variations, meaning the maximum deviation from the nominal sample per bin, averaged across $m_{\gamma\gamma}$ is taken as the scale uncertainty. As an example, Figure 6.31 shows the $m_{\gamma\gamma}$ distributions for the gg -interference samples, generated for each of the scale variations. This was undertaken at

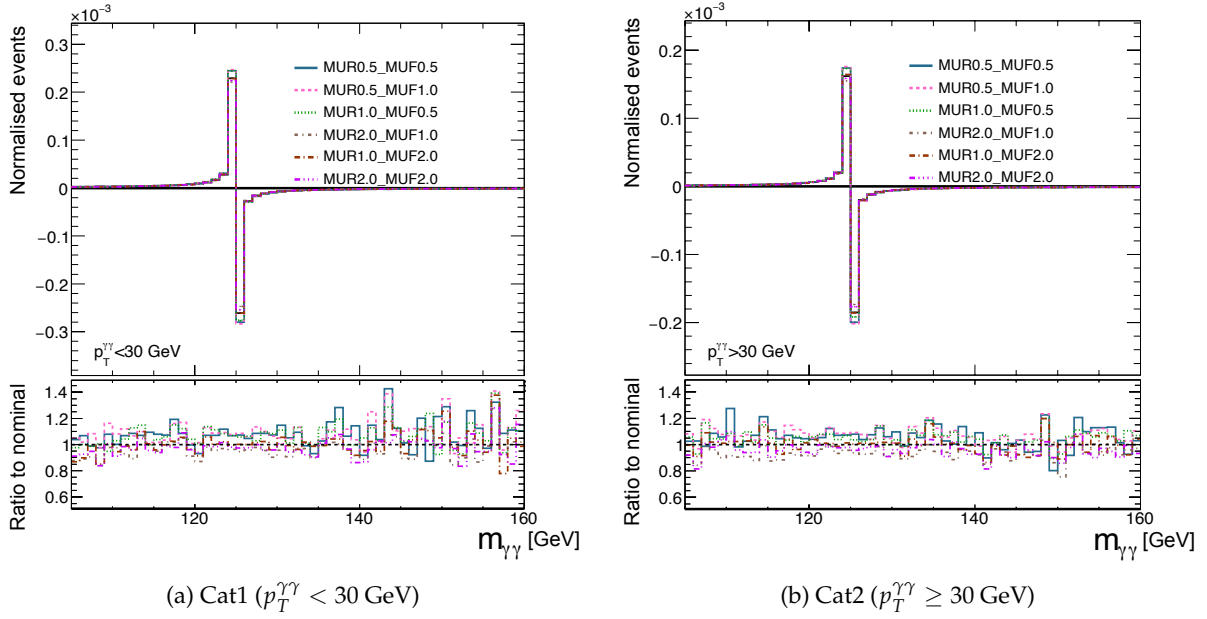


Figure 6.31: $m_{\gamma\gamma}$ distributions produced for the gg -interference process at different renormalisation and factorisation scales. Figure 6.31a corresponds to the variations in category 1, while Figure 6.31b is in category 2. The scale variations generated are listed in the legend where MUR corresponds to the value set for the renormalisation scale, μ_R , and MUF denotes the factorisation scale value, μ_F .

truth-level for each process, in each event category, where overall no shape effect on the $m_{\gamma\gamma}$ distribution was observed due to varying these scales, and thus affect only the overall yield. Table 6.20 contains the yield uncertainties corresponding to the scale variations for each process, which are around between 4 – 7% for the signal process, up to 8% for the gg -interference, and around 10% for the qg -interference.

Category	Signal	gg -interference	qg -interference
Cat1 ($p_T^{\gamma\gamma} < 30$ GeV)	4.3	7.9	10.9
Cat2 ($p_T^{\gamma\gamma} \geq 30$ GeV)	5.6	7.1	10.8

Table 6.20: Average maximum relative difference (expressed as a percentage %) between $m_{\gamma\gamma}$ distributions evaluated at different renormalisation and factorisation scales, evaluated for the signal gg - and qg -interference process for each event category.

Theoretical uncertainties due to the choice of parton density functions (PDFs) used during the generation must also be accounted for. These uncertainties derived from the precision with which the PDFs are known, as well as the imperfect knowledge of the strong coupling constant, α_s . These uncertainties are evaluated through a set of variations produced at generator level, where the impact on the $m_{\gamma\gamma}$ can be evaluated. In particular, a set of 30 variations are computed at generator level to determine the overall variation of $m_{\gamma\gamma}$ due to the PDF uncertainties. Two further variations are also computed, which correspond to varying the nominal values within its uncertainty within the measurement bound. The α_s value is taken from the measurement at m_Z : $\alpha_s(m_Z) = 0.1180 \pm 0.0015$ [3]. Overall these variations are observed to have a negligible impact on the $m_{\gamma\gamma}$ shape, and rather affect only the overall normalisation. As such, the final uncertainty associated with the PDF+ α_s variations is computed by taking the maximum deviation from the nominal in each $m_{\gamma\gamma}$ bin, and averaging this across the $m_{\gamma\gamma}$ distribution between 105 and 160 GeV. The computed values for the PDF+ α_s variations for the signal and interference processes are shown in Table 6.21, which vary between 4 – 11% in both categories.

Category	Signal	gg-interference	qg-interference
Cat1 ($p_T^{\gamma\gamma} < 30$ GeV)	4.2	11.1	6.2
Cat2 ($p_T^{\gamma\gamma} \geq 30$ GeV)	5.3	7.1	4.9

Table 6.21: Average maximum relative difference (expressed as a percentage %) between $m_{\gamma\gamma}$ distributions evaluated for the PDF+ α_s variations, evaluated for the signal gg- and qg-interference process for each event category.

6.8.4 Interference cross-section scale-factor uncertainty

The cross-section calculated for the interference processes by Sherpa is at NLO in QCD. The current best prediction for the interference cross-section however has been calculated at NNLOsv [41], as was introduced in section 3.3.3. To correct the NLO interference cross-sections to the more accurate NNLOsv predicted values, a scale factor will be applied to the NLO cross-section value. The magnitude of this scale factor was calculated in section 6.2.2 to be 1.65. This cross-section scale factor also comes with an associated theoretical uncertainty value. The reason for this is illustrated in Figure 6.32, which displays the cross-section on the gg-interference process at LO, NLO and NNLOsv. Cross-sections for Higgs boson decays in general are typically observed to be compatible only after NNLO accuracy. As such, when using a sample of events simulated at NLO accuracy but then applying a correction factor to the cross-section to effectively scale the cross-section to be at NNLOsv accuracy instead, an uncertainty on this correction factor must also be included. To be conservative, the magnitude of this uncertainty is taken as the relative

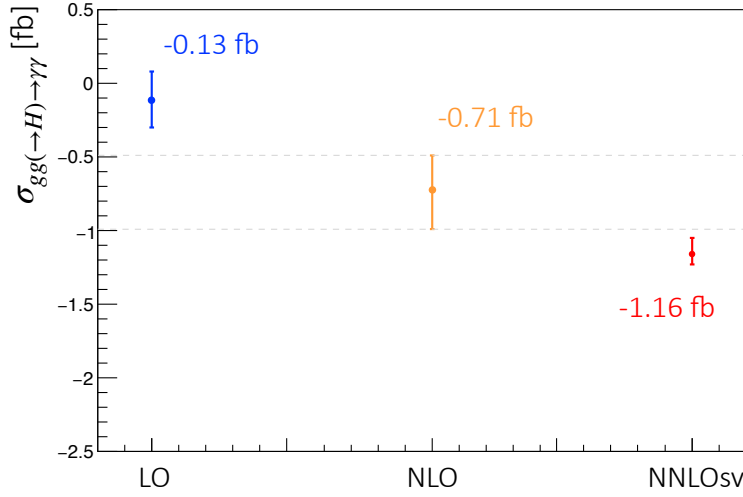


Figure 6.32: gg -interference cross-section values computed at LO, NLO and NNLOsv. The two grey horizontal lines indicate the $\pm 1\sigma$ uncertainty bands for the cross-section at NLO, which highlights the incompatibility between the calculated cross-sections at each of these three orders.

difference between the cross-section value computed at NLO and NNLOsv, i.e.

$$\frac{\sigma_{gg\text{-int.}}^{\text{NNLOsv}} - \sigma_{gg\text{-int.}}^{\text{NLO}}}{\sigma_{gg\text{-int.}}^{\text{NNLOsv}}} = \frac{-1.16 \text{ fb} - (-0.71 \text{ fb})}{-1.16 \text{ fb}} = 0.38 \quad (6.36)$$

This uncertainty is included as a nuisance parameter in the statistical model, for the gg -interference yield only.

6.8.5 MC generator initialisation parameters

As with any MC generated events, there are certain choices which must be made in the generation procedure, that affect the distribution of events in the observable of interest. Additional systematic uncertainties are evaluated to account for the impact of such choices on the measurement. A common strategy for evaluating the uncertainty due to a specific choice of MC generator is to simulate events with an alternate event generator, and compare the resulting difference in the kinematic distributions. The relative difference between the two distributions can then be included as a source of systematic uncertainty in the statistical model. Since this analysis has not been developed to such an extent before, there has not been significant development of the MC generation procedure and in fact, as mentioned in section 6.2.2, Sherpa is the only MC generator actually available which is able to simulate events for both of the relevant interference processes in the $\gamma\gamma$ channel. Given this, we must resort to other strategies to quantify the theoretical uncertainty associated with the Sherpa generation procedure. This section outlines one of the techniques used to achieve this via a variation in the initialisation parameters, while section 6.8.6 describes the method used to vary the choice of parton shower algorithm.

The default showering algorithm in Sherpa, the Catani-Seymour shower (CSS), is initialised through a number of parton shower settings, which depending on the selected value, can alter the shape of the resulting kinematic distributions. One such setting is the scale factor parameter for evaluating the strong coupling, labelled as `CSS_IS_AS_FAC`. This value is set to 1.0 during the MC generation procedure for this analysis, since better agreement was observed between the resulting $p_T^{\gamma\gamma}$ distributions when comparing events generated with Sherpa using this setting, and events generated with Powheg at NNLO precision. One way to probe the uncertainty associated with selecting this specific value, is to generate an additional sample setting `CSS_IS_AS_FAC` to an alternate value of 2.0 instead. This parameter is a scale factor which modifies the evaluation of the strong coupling constant; the effect of this in particular on the $p_T^{\gamma\gamma}$ distribution is to shift the peak of the distribution towards lower values when increasing the value of `CSS_IS_AS_FAC`. This suggestion came during private communication with the Sherpa authors, specifically Enrico Bothmann and Stefan Höche, where they advised this would sufficiently account for the variation in kinematics associated with the choice of `CSS_IS_AS_FAC` value.

A separate sample for each of the signal, gg - and qg -interference processes were generated at truth-level, setting `CSS_IS_AS_FAC`=2.0 in each case. The relative difference in $m_{\gamma\gamma}$ between these samples and the nominal samples used for the analysis, were calculated for each respective process. Given the large MC statistical fluctuations, particularly for the gg -interference sample, this is computed by taking difference between the two samples in each of the 55 bins in $m_{\gamma\gamma}$, and taking the average value. Overall no change in the $m_{\gamma\gamma}$ shape was observed, only an effect on the overall normalisation of the distribution is observed, which is therefore included as theoretical yield uncertainty for each process. The magnitude of this relative change is listed in Table 6.22 for each of the three processes, which correspond to the $+1\sigma$ change in yield, $\delta_{N_c}^{+1\sigma}$. The -1σ change is taken as $-1 \cdot \delta_{N_c}^{+1\sigma}$. The effect is less than 10% for all processes.

Category	Signal	gg -interference	qg -interference
Cat1 ($p_T^{\gamma\gamma} < 30$ GeV)	4.8	9.7	1.7
Cat2 ($p_T^{\gamma\gamma} \geq 30$ GeV)	6.5	7.9	1.3

Table 6.22: Average relative difference (expressed as a percentage %) between $m_{\gamma\gamma}$ distributions calculated using Sherpa MC simulated samples generated with `CSS_IS_AS_FAC`=2.0, compared to the nominal setting of `CSS_IS_AS_FAC`=1.0, evaluated at truth-level in each event category.

6.8.6 Parton shower algorithm

To probe the theoretical uncertainty associated with the parton shower in Sherpa, it would be ideal to use an alternative showering algorithm to understand the effect on the $m_{\gamma\gamma}$ distribution associated with the choice of algorithm. Sherpa does include a second shower implementation,

which is the DIRE algorithm [69, 121, 122]. Unfortunately this algorithm is not able to reliably generate interference events as there are already large known discrepancies between this algorithm and the default. This is displayed in Figure 6.10 of section 6.4, which placed restrictions on the appropriate choice of selection criteria to use to define the event categories used in this analysis. As a proxy for generating events with the Dire algorithm, the NLO_SUBTRACTION_SCHEME parameter will be altered instead. This parameter defines which types of divergences are subtracted off the amplitudes (both real and virtual), thus controlling whether the behaviour of the parton shower is more CSS-like, or more Dire-like, since this is one of the main differences between these implementations. The NLO_SUBTRACTION_SCHEME parameter was set to 2 to generate the analysis samples; alternate samples setting NLO_SUBTRACTION_SCHEME=0 will be used to evaluate the impact of such a choice. Ten million events were generated at truth level for each of the signal, gg -interference, and qg -interference processes with this setting of 0. Similarly to the procedure used in section 6.8.5, the ratio between $m_{\gamma\gamma}$ distributions obtained for this alternate sample, with respect to the nominal, will be computed and assigned as a systematic uncertainty. For all contributions, there was no significant $m_{\gamma\gamma}$ shape effects observed, and thus the computer difference (averaged across all bins in $m_{\gamma\gamma}$) will be used to define the respective $\pm 1\sigma$ yield uncertainties. The computed values are listed in Table 6.23, for each event category, where the impact is less than 1% for the signal process, less than 2% for the qg -interference process, and as expected much larger for the gg -interference process varying between 5%-10% for each category.

Category	Signal	gg -interference	qg -interference
Cat1 ($p_T^{\gamma\gamma} < 30$ GeV)	0.05	5.95	1.13
Cat2 ($p_T^{\gamma\gamma} \geq 30$ GeV)	0.02	9.94	1.89

Table 6.23: Average relative difference (expressed as a percentage %) between $m_{\gamma\gamma}$ distributions calculated using Sherpa MC simulated samples generated with NLO_SUBTRACTION_SCHEME=0, compared to the nominal setting of NLO_SUBTRACTION_SCHEME=2, evaluated at truth-level in each event category.

6.8.7 Modelling bias uncertainties

Analytical functions have been used to model the $m_{\gamma\gamma}$ distributions for each of the signal, interference, and background contributions, as described in sections 6.5 - 6.7 respectively. For each process, the specific function chosen has been selected since it provides the best description of the simulated data, compared to the other functions tested. Once the free parameters of the respective models have been selected, they are no longer free to float when fitting to data. The only exception to this is the shape and parameters for the chosen background function, however in this case the actual function used is also already fixed. This means that a mis-modelling of the contributions when fitting the data is possible, which derives from the inherent imperfect knowledge of the shape of the individual contributions, when fitting to data. This mis-modelling can

cause a bias in the measurement, and hence must be evaluated such that a systematic uncertainty can be included to account for this bias.

An estimate of the bias is achieved by performing an *injection test*, for each of the signal, interference, and background. Taking the signal as an example, the injection test procedure proceeds as follows. A dataset consisting of interference and background Asimov is defined and the MC simulated signal histogram is *injected* into this dataset, meaning the bin contents of the Asimov are summed per bin with the bin contents of the signal MC. The nominal total PDF model (equation 6.2), defined by summing the individual signal, interference and background models as described in sections 6.5 - 6.7, is fitted to this dataset. The signal bias is computed by taking the relative shift between the fitted and injected ($\lambda = 1$) value of the Higgs boson width. During this procedure the signal strength and Higgs boson mass parameters are fixed at $\mu = 1$ and $m_H = 125.0$ GeV. This test is then again repeated with a $\lambda = 100$ value for the Higgs boson width instead, to also verify the behaviour at large Higgs boson width values. The larger of the two biases is then included as the uncertainty.

This entire procedure is undertaken separately for each of the relevant processes, just substituting the signal for the relevant process where applicable. The results obtained for each process are outlined below. Ultimately one bias uncertainty is included per process as a nuisance parameter in the statistical model. To check for consistency, the same test is repeated also for the μ and m_H parameters. This is used as an additional check to confirm the parameter values set when creating the Asimov dataset are retrieved back again during the injection test. As will be shown in the following results sections, this is indeed the case, the discrepancy is below 1% in all cases and hence no additional uncertainty is applied.

Signal modelling uncertainty: The results of the signal injection test are displayed in Table 6.24a and 6.24b corresponding to the biases evaluated for $\lambda = 1$ and $\lambda = 100$ respectively. The larger bias is observed for $\lambda = 100$, at a value of 7.72%. The injection tests results undertaken for the μ and m_H parameters are also displayed, where no significant discrepancy was observed for either λ value.

Interference modelling uncertainty: The evaluation of potential biases in the measurement due to the interference contributions are evaluated by considering the combined gg - and qg -interference. The results and computed biases are displayed in Table 6.25, for both $\lambda = 1$ and $\lambda = 100$ hypotheses. The largest evaluated bias is 12.61%, which is assigned as the interference modelling uncertainty.

Background modelling uncertainty: To estimate the background bias, the same background templates as per the spurious signal evaluation (determined in section 6.7.1) are again used here

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	0.98	0.99	0.88
μ	1.00	0.99	-1.04
m_H	124.99 GeV	124.99 GeV	0.00

(a) $\lambda = 1$

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	100.67	108.44	7.72
μ	1.00	0.99	-1.01
m_H	124.98 GeV	124.97 GeV	-0.01

(b) $\lambda = 100$

Table 6.24: Results of the signal injection test used to quantify the modelling bias uncertainty associated with the choice of function used to described the signal process. Figure 6.24a corresponds to the $\lambda = 1$ hypothesis, while Figure 6.24b is instead λ .

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	0.98	1.08	9.26
μ	1.00	1.00	-0.01
m_H	124.99 GeV	124.99 GeV	0.00

(a) $\lambda = 1$

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	100.67	115.20	12.61
μ	1.00	0.99	-1.02
m_H	124.98 GeV	125.33 GeV	0.28

(b) $\lambda = 100$

Table 6.25: Results of the interference injection test used to quantify the modelling bias uncertainty associated with the choice of function used to described the interference processes. Figure 6.25a corresponds to the $\lambda = 1$ hypothesis, while Figure 6.25b is instead λ .

for the background MC. The results obtained for the background injection test are displayed in Table 6.26, where again separate tests considering both $\lambda = 1$ and $\lambda = 100$ hypotheses have been performed. The largest bias due to background mis-modelling is 10.34%, which is included as a single nuisance parameter.

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	0.98	0.92	-6.04
μ	1.00	0.98	-2.00
m_H	124.99 GeV	125.03 GeV	0.03

(a) $\lambda = 1$

Fitted parameter	Fitting Asimov	Injection test fit	Relative difference [%]
λ	100.67	111.08	10.34
μ	1.00	0.98	-2.00
m_H	124.98 GeV	125.33 GeV	0.28

(b) $\lambda = 100$

Table 6.26: Results of the background injection test used to quantify the modelling bias uncertainty associated with the choice of function used to described the background process. Figure 6.26a corresponds to the $\lambda = 1$ hypothesis, while Figure 6.26b is instead λ .

All of the respective systematic uncertainties described and evaluated within this section are included as nuisance parameters in the statistical model, which will be detailed in the following section.

6.9 Statistical model

The maximum likelihood estimate for a given parameter ψ is often determined by evaluating the log-likelihood function (actually usually -2 times the log-likelihood) for various values of ψ over a defined range, and finding the one which minimises this $-2\log L$ quantity. Performing such a likelihood *scan* is the method often used to identify ψ , and was undertaken in section 6.4 to ascertain which event categorisation scenario provided the best sensitivity to the parameter of interest, λ . The accuracy with which this ψ is determined through this likelihood scan is quantified by the $\pm 1\sigma$ uncertainty values, which are calculated by varying ψ from its minimum value by an amount which equates to deviating $-2\log L$ by 1 either side of the minimum value, i.e. $\Delta[-2\log L] = 1$.

If there is more than one free parameter in the likelihood function, finding the best-fit value for each of these parameters can become difficult. Consider the case where the PDF is defined in terms of a parameter of interest λ , along with a set of nuisance parameters θ ; the log-likelihood is defined as:

$$\log L(x; \lambda, \theta) = \sum_{i=1}^n \log f(x_i; \lambda, \theta). \quad (6.37)$$

In this example the parameter we wish to measure is λ however the set of additional parameters θ must also be estimated. This is achieved by first fixing the parameter λ to a given value, and then evaluating the minimum of the log-likelihood function $\log L_\lambda(\theta)$ for each nuisance parameter θ . This results in a set of likelihood curves, one for each θ . This procedure can be repeated for a range of λ values. The parameter of interest λ is subsequently estimated by choosing the value which corresponds to the minimum over all likelihood curves. This method is known as *profiling*, since the nuisance parameters are first profiled over and then the parameter of interest is estimated. This method is especially useful when including systematic uncertainties, since they're included in the likelihood function as nuisance parameters.

An extended likelihood function $\mathcal{L}$ is built to model the data using the signal, interference and background functions described in section 6.5, section 6.6 and section 6.7 and the constraints coming from the systematic uncertainties described in section 6.8. The inclusion of the interference processes in the total PDF provide the largest sensitivity to the Higgs boson width, and allow us to constrain Γ_H in this analysis. The models, each with their respective systematic uncertainties, are combined together in the following likelihood function, which is built to model the data for each event category c :

$$\mathcal{L}(\lambda, \mu, m_H, \theta; m_{\gamma\gamma}) = \prod_{c=1}^{N_c} \text{Pois}(n_c | \nu^c(\lambda, \mu, \theta)) \prod_{i=1}^{n_c} f_c(m_{\gamma\gamma}^i; \lambda, m_H, \theta) \prod_j G(\alpha_j | \theta_j, 1). \quad (6.38)$$

The first product is the extended likelihood term which spans the number of categories N_c , where the number of observed events for each category n_c is modelled with a Poisson distribution with mean defined by:

$$\nu^c(\lambda, \mu, \theta) = \mu K_S N_S^c(\theta) + \sqrt{\mu \lambda K_S} K_I N_I^c(\theta) + N_B^c, \quad (6.39)$$

where $K_S = 1.4$ is a scale factor applied to correct for missing higher order terms in the cross-section calculation [3], as introduced in section 6.2.2. This scales the signal yield by K_S , and the interference yields by $\sqrt{K_S}$. The $K_I = 1.65$ factor instead scales the gg -interference yield to the best predicted value for the cross-section at NNLOsv (note this factor is *only* applied to the gg -interference yield), as introduced in section 6.2.2. The number of signal events in each category is given by:

$$N_S^c(\theta) = \sum_p \sigma_p^{\gamma\gamma}(\theta) \cdot L(\theta_{\text{lumi}}) \cdot \epsilon^c(\theta) \cdot K_c(\theta) + N_{\text{spur}}^c \theta_{\text{spur}}^c, \quad (6.40)$$

where

- $\sigma_p^{\gamma\gamma}$ are the values of the branching ratio for the $H \rightarrow \gamma\gamma$ decay, multiplied by the Higgs boson production mode p cross section, for a Higgs boson with mass $m_H = 125.0$ GeV;
- L is the integrated luminosity of the fitted sample, with associated NP θ_{lumi} ;
- θ denotes the set of NPs in each respective category that impact the yield;

- ϵ^c is the signal efficiency vector, which parametrises the probability for a truth-level Higgs boson event ending up in category c ;
- $K_c(\theta)$ is a vector of multiplicative correction factors to the signal yields, as a function of the NPs;
- N_{spur}^c is a vector of values of the background modelling uncertainty described in Section 6.7, implemented as an additive correction to the signal yield proportional to the NP θ_{spur}^c .

Similarly, the number of interference events (for each of the gg - and qg - interference contributions) in category c is given by:

$$N_I^c(\theta) = \sigma_I^{\gamma\gamma} \cdot L(\theta_{\text{lumi}}) \cdot \epsilon_I^c(\theta) \cdot K_c(\theta), \quad (6.41)$$

where

- $\sigma_I^{\gamma\gamma}$ is the value of the $H \rightarrow \gamma\gamma$ branching ratio multiplied by the respective interference cross section;
- ϵ_I^c is the interference efficiency vector, for category c ;
- K_c are the set of yield correction factors to be applied to the interference cross-section, for each category.

The second product term in the likelihood function (equation 6.38) corresponds to the probability density functions (PDF) of the individual signal, interference, and background functions in each category, c . As introduced in equation 6.2 in section 6.1, the total PDF is more explicitly defined as:

$$\begin{aligned} f_c(m_{\gamma\gamma}^i; \lambda, \mu, m_H, \theta) = \frac{1}{\nu_c} \Big[& \mu \cdot N_S^c(\theta_{\text{yield}}) \cdot f_S^c(m_{\gamma\gamma}^i; m_H, \theta_{\text{shape}}) \\ & + \sqrt{\mu\lambda} \cdot N_{I(gg)}^c(\theta_{\text{yield}}) \cdot f_{I(gg)}^c(m_{\gamma\gamma}^i; \lambda, m_H, \theta_{\text{shape}}) \\ & + \sqrt{\mu\lambda} \cdot N_{I(qg)}^c(\theta_{\text{yield}}) \cdot f_{I(qg)}^c(m_{\gamma\gamma}^i; \lambda, m_H, \theta_{\text{shape}}) \\ & + N_B^c \cdot f_B^c(m_{\gamma\gamma}^i; \theta_{\text{BS}}) \Big], \end{aligned} \quad (6.42)$$

where

- $\lambda = \frac{\Gamma_H}{\Gamma_{SM}}$ is the ratio of the measured Higgs boson width to the SM expectation. It is the parameter of interest (POI) of the model and its (upper) error from the fit will be used to set a(n upper) limit on Γ_H ;
- μ is the signal strength, which parametrises the agreement between the measured cross-section and the Standard Model prediction. It can be either set to 1 (perfect agreement with the SM) or, to be more model-independent, can be left free-to-float, thus producing an additional nuisance parameter (NP). Fit results will be provided in both configurations;

- m_H is the Higgs boson mass parameter. It can be either set to 125.0 GeV (the value of the most precise mass measurement so far) or, to be more assumption-free, can be left free-to-float in the model, thus providing an additional NP. Fit results will be provided in both configurations;
- f_S is the signal function, as described in section 6.5. The parameters describing the signal shape are fixed in the fit to the data, to those obtained when fitting the MC simulated events. The only exceptions to this are when m_H or λ are free-to-float which can shift the position or change the resolution of the signal peak respectively. NPs associated to the shape systematic uncertainties (θ_{shape}) can affect the position and width of the signal peak;
- $f_{I(gg)}, f_{I(qg)}$ are the gg -, qg -interference functions respectively, as described in section 6.6. In the fit to data, the variation in shape of the interference distribution due to the Higgs boson width is controlled by λ . The Higgs boson mass, m_H , can shift the position of the entire lineshape, when free-to-float in the fit. NPs associated to the shape systematic uncertainties (θ_{shape}) can affect the position and width of the lineshape;
- f_B is the background function where, as described in section 6.7, an ExpPoly2 function is used to model the background in both of the event categories. The two background shape parameters θ_{BS} and the background normalisation N_B (one per category) are NPs in the fit to the data;

The final term in the likelihood is the product of constraint terms, the forms of which were introduced in section 6.8 and are listed in equations 6.29 - 6.30. Each NP θ_j , with the exception of θ_{BS} is constrained by an unitary Gaussian PDF $G(\theta)$ of width 1. The two background shape parameters are unconstrained. The global observable α in equation 6.38 corresponds to the mean value, which is usually set to zero. The number of nuisance parameter and their respective constraints are reported in Table 6.27.

The profile likelihood ratio (PRL) is used as the test statistic to perform the desired measurement, and is defined as:

$$\text{PRL}(\lambda, m_H, \mu) = -2 \ln \frac{\mathcal{L}(\lambda, m_H, \mu, \hat{\theta}_{\lambda, m_H, \mu})}{\mathcal{L}(\hat{\lambda}, \hat{m}_H, \hat{\mu}, \hat{\theta})} \quad (6.43)$$

where $\hat{\lambda}$, $\hat{m}_H$, $\hat{\mu}$ and $\hat{\theta}$ are the parameters for which the likelihood is maximised unconditionally [102], and $\hat{\theta}_{\lambda, m_H, \mu}$ denotes the nuisance parameter values which maximise the likelihood in the case where the λ , m_H , and μ parameters are fixed (to $\lambda = 1$, $m_H = 125$ GeV and $\mu = 1$).

The model in equation 6.42 is fitted with a simultaneous maximum likelihood fit over a uniformly binned dataset in with 550 bins (100 MeV per bin), for both the (simulated) Asimov and the real dataset. The index i in the likelihood function (equation 6.38) denotes the iteration over these bins in $m_{\gamma\gamma}$. The bin size is optimised as a trade-off between being able to measure the effects of small

	Systematic source	NP	Implementation
Yield and migration	Luminosity	1	$N_{\text{tot}} F_G(\delta_i, \theta_i)$
	Branching ratio	1	$N_{\text{tot}} F_G(\delta_i, \theta_i)$
	QCD Scale	1	$N_c F_G(\delta_i, \theta_i)$
	PDF+ α_s	1	$N_c F_G(\delta_i, \theta_i)$
	Parton shower initialisation	1	$N_c F_G(\delta_i, \theta_i)$
	Parton shower algorithm	1	$N_c F_G(\delta_i, \theta_i)$
	Photon Trigger	1	$N_c F_G(\delta_i, \theta_i)$
	Photon Isolation	1	$N_c F_G(\delta_i, \theta_i)$
	Photon Identification	1	$N_c F_G(\delta_i, \theta_i)$
	Photon Scale	1	$N_c F_G(\delta_i, \theta_i)$
	Photon Resolution	1	$N_c F_G(\delta_i, \theta_i)$
	Pileup	1	$N_c F_G(\delta_i, \theta_i)$
Shape	Photon Scale	1	$\mu_{\text{CB}} F_G(\delta_i, \theta_i)$
	Photon Resolution	1	$\sigma_{\text{CB}} F_G(\delta_i, \theta_i)$
	Signal Bias	1	$N_{\text{tot}} F_G(\delta_i, \theta_i)$
	Background Bias	1	$N_{\text{tot}} F_G(\delta_i, \theta_i)$
	Interference Bias	1	$N_{\text{tot}} F_G(\delta_i, \theta_i)$
Bkg	Spurious signal	2	$N_{\text{spur},c} \theta_{\text{spur},c}$

Table 6.27: Summary of included systematic uncertainties δ_i along with their implementation in the likelihood function, impacting on signal and interference yields, mass scale/resolution and the spurious signals resulting from the background parametrisation. N_{tot} indicates that the uncertainty affects only the overall yield for each process, while N_c implies the yield impact is evaluated per analysis category, c .

systematic uncertainties, but not being so small so to incur large statistical fluctuations. The λ POI is estimated through this maximum likelihood fit, over all defined analysis categories. The expected results obtained by fitting the Asimov dataset are presented in section 6.10.1, while the results when fitting to the Run 2 dataset are presented in section 6.10.2.

6.10 Results

This section presents the expected (section 6.10.1) and observed (section 6.10.2) results corresponding to the Higgs boson width determination. Results of the simultaneous maximum likelihood fit to the $m_{\gamma\gamma}$ distribution in all analysis categories are provided for three configurations of the statistical model:

Configuration 1: λ is the only free-to-float POI, while the signal is assumed to have SM yield ($\mu = 1$) and the Higgs boson mass is set to $m_H = 125.0$ GeV;

Configuration 2: λ is the free-to-float POI and μ is profiled, while the Higgs boson mass is set to $m_H = 125.0$ GeV;

Configuration 3: λ is the free-to-float POI, μ and m_H are profiled.

Configuration 1 produces a result with the most assumptions, give both the μ and m_H parameters are fixed to their expected value. Alternatively, Configuration 3 produces the most assumption-free result, given all parameters are free-to-float. Results for all three fit configurations will be presented, such that the obtained measurement of the Higgs boson width in each case can be compared. It is however expected that Configuration 1 will produce the most constrained upper limit on the width, given there are less free parameters floating.

6.10.1 Expected results

The expected results are obtained through a fit to an Asimov dataset (introduced in section 6.2.1), generated from the constructed total PDF (introduced in section 6.9) where the parameters are set to: $\lambda = 1$ (SM expectation), $\mu = 1$ (SM expectation) and $m_H = 125.0$ GeV. To construct the Asimov dataset, the normalisation and shape parameters of the background are initialised through a background-only fit to the data sidebands, excluding the signal region from 120 to 130 GeV. The plots of the fit to the data sidebands are given in Figure 6.25, and the normalisation values are presented in Table 6.15. Distributions for the total-model fit to the Asimov data are given in Figure 6.33 for each event category.

A likelihood scan is performed over λ , for $\lambda \in [0, 200]$, where the upper error at the 2σ level on λ , is considered a proxy of the limit at the 95% confidence level (C.L.). The limit on λ is presented in Table 6.28, where the fit is repeated for different configurations. The likelihood scans corresponding to each of these configurations is shown in Figure 6.34. To probe the shape of this

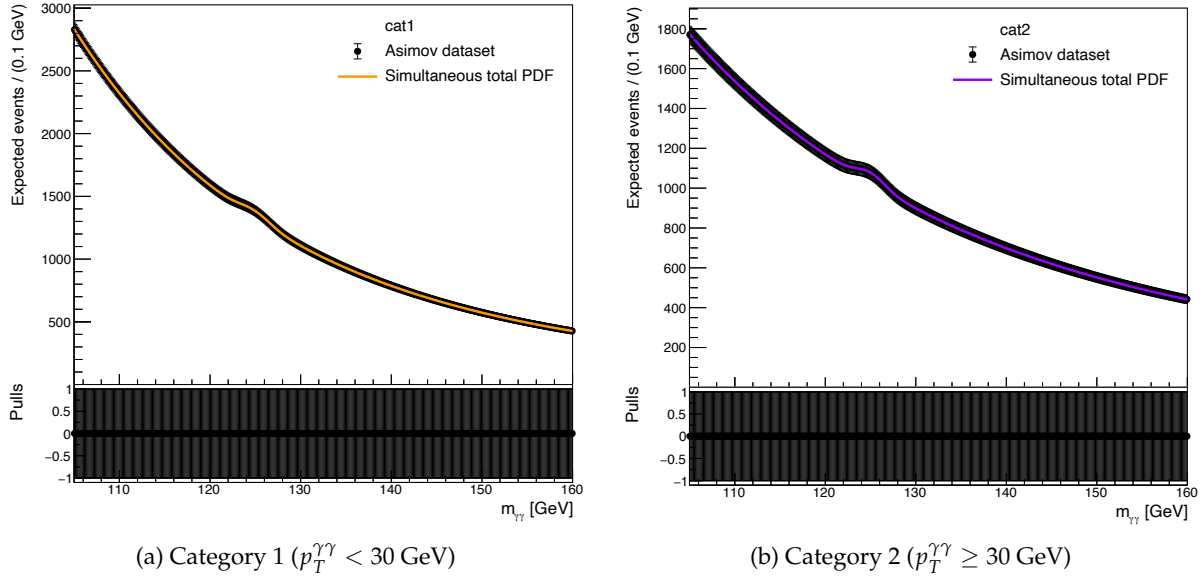


Figure 6.33: Generated Asimov dataset in each of the two analysis categories, Figure 6.33a displays category 1, and Figure 6.33b corresponds to category 2, where the total PDF is fitted to the dataset in each case.

likelihood, a more zoomed in version of this result was also checked, to verify that the expected parabolic nature of the likelihood function is observed, which indeed it was, at very small λ values such as $\lambda \in [0, 4]$.

	Scan/profile over	U.L. on λ at 95% C.L.	U.L. on Γ_H
Stat-only	λ	20.3	82.9 MeV
	λ, μ	20.3	83.0 MeV
	λ, μ, m_H	25.7	104.9 MeV
System.	λ	59.2	242.0 MeV
	λ, μ	59.7	244.3 MeV
	λ, μ, m_H	80.7	329.9 MeV

Table 6.28: Upper limit on λ obtained from the fit to the Asimov dataset. This value is reported for different fit configurations, as detailed in the first column. The first three rows report stat-only fit results, while the final three rows correspond to the results including systematic uncertainties.

Both the signal strength and the Higgs boson mass value have been determined now very precisely experimentally. Since our constraining power on these parameters is quite weak, we do not learn so much about these parameters in our analysis. The best sensitivity we achieve is with these parameters fixed at $\mu = 1$ (the SM expectation which is compatible with experimental observations) and $m_H = 125.09$ GeV (the best fit value obtained by the Run 1 ATLAS and CMS mass measurement combination), which is $\Gamma = 59.2 \cdot \Gamma_H^{\text{SM}}$ at 95% C.L. The nuisance parameter ranking plot obtained in this fit configuration is displayed in Figure 6.35, where the uncertainty on the gg -interference yield is observed to have the largest impact. This particular systematic uncertainty

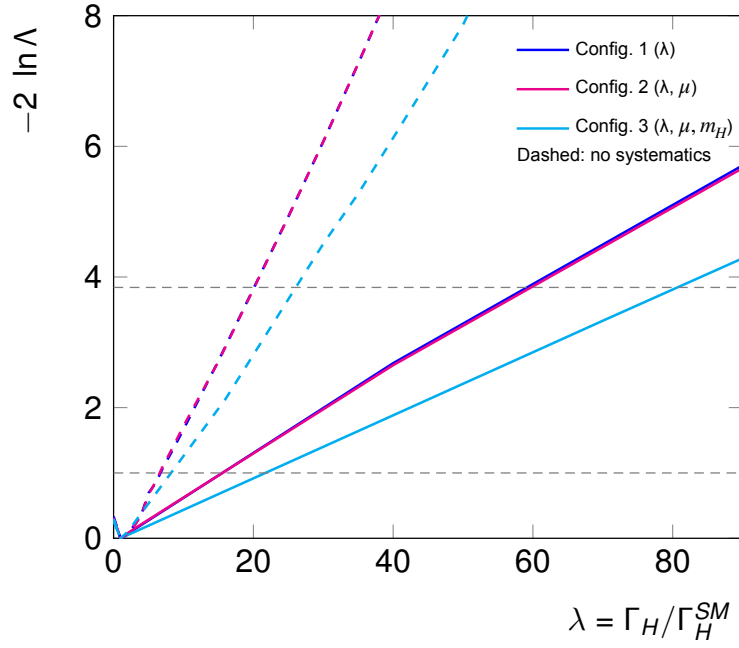


Figure 6.34: Likelihood scan over λ the Higgs boson width POI, considering three different fit configurations. The dashed lines indicate the fit is statistical only, while the solid lines include all systematic uncertainties. The horizontal grey lines indicate the 1σ and 2σ crossing values for the $-2\ln\Lambda$ functions which are used as a proxy for the 68% and 95% confidence levels respectively.

is expected to have an asymmetric impact, since the λ value in the fit cannot be negative (would correspond to a negative value for the Higgs boson width which is not physical), and so can vary more in the positive direction than the negative one.

The impact of the shape uncertainties associated with the photon energy scale and resolution are not included in this plot since during the evaluation of these two shape uncertainties it was observed that they were overconstrained during the fit. This means likely the combined photon energy scale (PES) and photon energy resolution (PER) systematics are under-estimated. The main avenue for resolving this would be, instead of using this simplified 2 NP model, to use the *Full NP Model* provided by the ATLAS e/γ calibration group, which consists of 70 individual nuisance parameters for the PES and 9 for the PER. These would all vary individually as shape systematics, thus each of their impacts would be smaller than the combined single PES and PER NPs. Since the systematics affect the shape of the signal and interference processes, this would mean extending the morphing functions used to describe the two interference contributions by an additional 79 dimensions. This makes the statistical model significantly more complicated, with many more degrees of freedom in the fit. It is observed that the impact due to the PES and PER systematics implemented for this analysis are on the same order of magnitude as the effect of floating the Higgs boson mass in the statistical fit (excluding systematics), so quite significant compared to the effects of other uncertainties. Many of the most impactful systematic uncertainties derive from theoretical uncertainties in the MC generation procedure, which is unsurprising given the

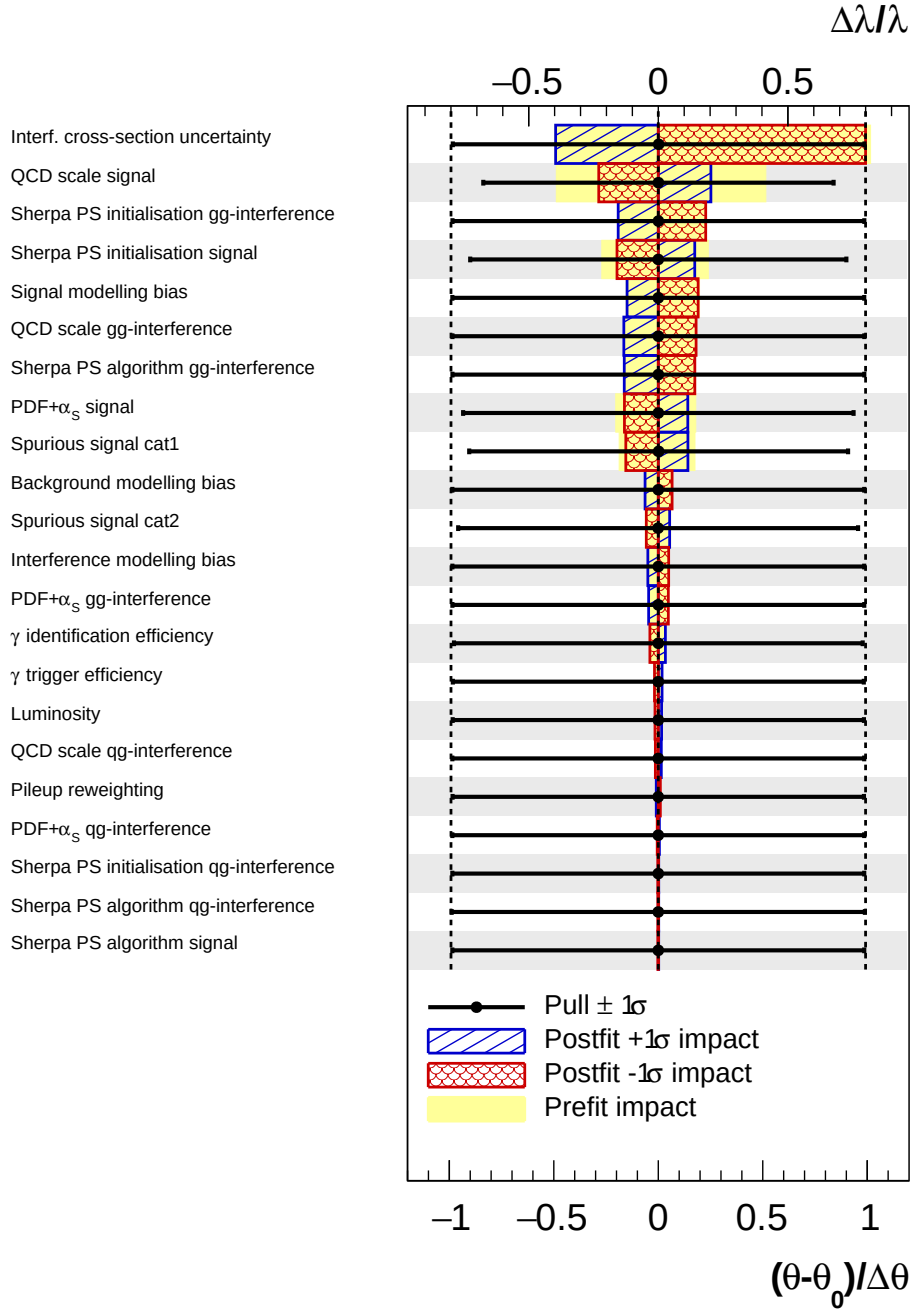


Figure 6.35: Ranking of the nuisance parameters according to their impact on λ .

magnitude of observed impact during the evaluation of such uncertainties in section 6.8.

6.10.2 Observed results

The observed results are obtained following the same procedure undertaken for the expected results presented in the previous section, but performed on the data collected by the ATLAS detector instead of the constructed Asimov dataset. The background shape and overall normalisation

parameters for each event category are obtained from fitting the data in the sidebands regions. Figure 6.36 displays the $m_{\gamma\gamma}$ distribution observed in data, for each of the two analysis categories, where the total simultaneous PDF model is shown fitted to the data in each case. The observed

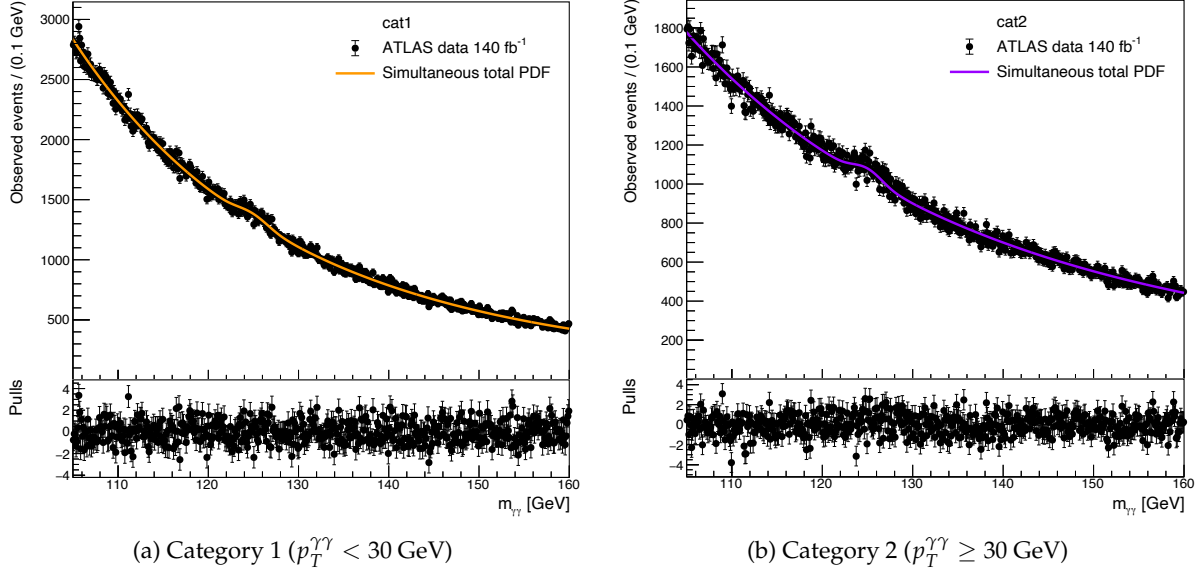


Figure 6.36: Invariant diphoton mass distributions using the ATLAS Run 2 dataset; Figure 6.36a displays category 1, and Figure 6.36b corresponds to category 2, where the total PDF is fitted to the dataset in each case.

results are shown in Table 6.29, where the same three fit configurations used to obtain the expected results are displayed. As expected, the results for configuration 1 provide the best sensitivity to the Higgs boson width POI λ , where the observed constraint is $\Gamma_H < 54.1 \cdot \Gamma_H^{\text{SM}}$ at the 95% C.L.

	Scan/profile over	U.L. on λ at 95% C.L.	U.L. on Γ_H
Stat-only	λ	16.1	66.0 MeV
	λ, μ	16.1	65.9 MeV
	λ, μ, m_H	22.1	90.4 MeV
System.	λ	54.1	221.3 MeV
	λ, μ	54.2	221.7 MeV
	λ, μ, m_H	76.7	313.7 MeV

Table 6.29: Upper limit on λ obtained from the fit to data, in three different fit configurations.

6.11 Measurement prospects and future improvements

The sensitivity to the Higgs boson width through the evaluation of interference effects is particularly limited by the statistical uncertainty, which will be significantly reduced upon collection of the full high-luminosity (HL-LHC) expected dataset of 3000 fb^{-1} . This section presents a study

conducted to project the existing analysis sensitivity to the Higgs boson width, to that expected by the end of the HL-LHC data-taking period.

The projection study extrapolates from the expected results presented in section 6.10.1 to account for the increase in data, as well as the impact of the expected increase in centre-of-mass energy with which the proton collisions will occur, $\sqrt{s} = 14$ TeV. This study proceeds by scaling the following parameters:

- Scale the luminosity by a factor $3000 \text{ fb}^{-1} / 140 \text{ fb}^{-1} = 21.4$;
- Scale the signal cross-section by a factor 1.13 to account for the increase in $\sqrt{s}$ from 13 TeV to 14 TeV [3];
- Scale the background cross-section by a factor 1.18 to account for the increase in $\sqrt{s}$ from 13 TeV to 14 TeV [3];
- Scale the interference cross-section to account for the increase in $\sqrt{s}$; in this case a factor $\sqrt{1.13 \times 1.18}$ is used corresponding to the square root increase of the product of the individual increases in the signal and background cross-sections, since there is no interference cross-section available at $\sqrt{14}$ TeV;
- Reduce the statistical uncertainty on the Higgs boson mass, m_H , used to apply the Gaussian constraint for the mass value, by a factor of 4.6. This is due to the increase in luminosity only; the systematic uncertainty component to the mass value has remained fixed.

It is assumed that efficiencies associated to object reconstruction, trigger, and identification at the HL-LHC are all identical to that used in the Run 2 analysis, meaning no adjustments have been made to these during the projections. There have also been no reductions on the systematic uncertainties included. It is worthy to note that one of the leading sources of systematic uncertainties in the present full Run 2 analysis is the theoretical uncertainty on the gg -interference cross-section. Private communications with the relevant theorists indicate they are currently working on a complete NNLO calculation of the interference cross-sections, which would already allow for a reduced uncertainty compared to that included in section 6.8. In general the coming decades of work also from the theory side will greatly assist in reducing the leading sources of systematic uncertainties in this analysis, thus allowing the experimental sensitivity to increase further.

This projection study has also not accounted for the plethora of improvements which could be made in the analysis, for example in the event categorisation. Investigations could be made into more analysis categories which take into account for example the conversion status of the photons or the dependance on η , particularly when there is more data available to sufficiently populate these categories, which would likely also bring improvements to the sensitivity. Additionally

the inclusion of a dedicated VBF region would also allow for increased sensitivity since it would provide an additional category of events within the $\gamma\gamma$ channel [52], as outlined in section 3.3.4. This would require further developments in the MC generation procedure which is currently not straightforward for $pp \rightarrow H(\rightarrow \gamma\gamma) + 2 \text{ jet events}$.

The projected sensitivity to the Higgs boson width, with the full HL-LHC dataset, is detailed in Table 6.30. In this case the μ and m_H are also profiled over in the fit, to be as general as possible (corresponding to configuration 3 of the fit, as introduced in section 6.10). The constraining power is expected to increase by roughly a factor six with respect to the Run 2 results, yielding an upper limit on the Higgs boson width of $\Gamma_H < 13.9 \cdot \Gamma_H^{\text{SM}}$ at the 95% C.L.

$\sqrt{s}$	$\int L \cdot dt$	Scan/ profile over	U.L. on λ at 95% C.L.	U.L. on Γ_H at 95% C.L.
14 TeV	3000 fb ⁻¹	λ, μ, m_H	9.6	39.2 MeV
14 TeV	3000 fb ⁻¹	$\lambda, \mu, m_H, + \text{systematics}$	13.9	56.4 MeV

Table 6.30: Sensitivity to the Higgs boson width expected at the end of the HL-LHC data-taking period. Upper limits have been provided when considering statistical uncertainties only (first line), as well as the expected result including systematic uncertainties (second line).

6.12 Conclusion

This chapter has presented the analysis to determine the Higgs boson width in the diphoton final state using the Run 2 dataset collected by ATLAS, corresponding to a total integrated luminosity of 140 fb⁻¹. Interference effects between the resonant signal and continuum background processes cause measurable shape changes and total yield differences in the diphoton invariant mass distribution, $m_{\gamma\gamma}$, which are known to vary as a function of the Higgs boson total width, Γ_H . This novel measurement technique was exploited in the presented analysis. The observed (expected) upper limit on the width parameter for configuration 1 is found to be $\lambda < 54.1$ (59.2) at a 95% C.L., corresponding to a constraint on the Higgs boson decay width of $\Gamma_H < 221.3$ MeV (242.0 MeV) at a 95% C.L. Although this result is significantly larger than the SM predicted value, interferometry provides a complementary measurement method which has allowed for an additional independent determination of the Higgs boson width. The measurement uncertainty is significantly dominated by the statistical component. The LHC is scheduled to be upgraded to a high-luminosity version in the coming years, where an estimated total integrated luminosity of 3000 fb⁻¹ is anticipated to be collected by the ATLAS detector. This factor of roughly 20 times increase in data will see the single biggest reduction to the uncertainty of the presented Higgs boson width measurement. Section 6.11 presents a projection study conducted to estimate the sensitivity improvement that could be placed on the Higgs boson total width using interferometry with the HL-LHC dataset. Chapter 7 will discuss this high-luminosity upgrade of the LHC,

and the upgrade activities that are already underway to prepare the ATLAS detector for this new era.

7 | The High Luminosity Large Hadron Collider

To gain a better understanding of the Higgs boson's properties, and to improve the experimental reach of beyond the SM physics searches, the existing LHC will be upgraded to a higher luminosity version. The high-luminosity LHC (HL-LHC) upgrade will include a centre-of-mass energy increase to $\sqrt{s} = 14$ TeV, as well as an increase in the peak instantaneous luminosity up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The integrated luminosity expected by the end of the HL-LHC data-taking period (2040+) is 3000 fb^{-1} [123], which corresponds to a roughly 20 times increase in the dataset size compared to that collected during Run 2. This larger dataset will significantly improve the detection likelihood of rare events, as well as lowering the statistical uncertainties of existing measurements. These improvements are necessary for precision measurements of various Higgs boson properties, for example in determining the width in the $H \rightarrow \gamma\gamma$ channel given the current statistical limitations as seen in Chapter 6.

One major challenge associated with the increase in instantaneous luminosity is the subsequent increase in the average number of interactions per bunch crossing, known as *pileup*, $\langle\mu\rangle$. This quantity is defined in terms of various beam parameters including the bunch population, the crossing angle between colliding beams, the beam dimensions, as well as the instantaneous luminosity [124]. The mean pileup value during Run 2 was approximately $\langle\mu\rangle = 33$. Given the peak instantaneous luminosity anticipated during the HL-LHC, this mean value is expected to climb to around 130 - 190. The maximum pileup value for a given HL-LHC event is expected to reach $\langle\mu\rangle = 200$ [123]. An example of such an event at the HL-LHC is shown in Figure 7.1. This figure depicts a 3D event display of a potential $\langle\mu\rangle = 200$ event with the simulated charged particle tracks measured in the ITk shown in pink, to give an indication of the complexity of such an event.

If sufficient increases in detector granularity are not made, the current track finding efficiency, as well as the ability to resolve nearby tracks, will be severely compromised by an increase in the average number of proton-proton interactions per bunch crossing. There is also the issue of fake tracks: fake tracks are defined as being a random combination of hits in the detector which the track finding algorithm has incorrectly labelled as a track. The hits themselves may be real, and just deriving from independent tracks that have been incorrectly grouped together, or they could

be ghost hits, meaning the detector recorded a hit when in fact no particle passed traversed the detector. The rate of fake tracks will increase dramatically, given the larger number of charged particles traversing the detector, and the detectors inability to technically cope with such conditions. These detector occupancy limitations necessitate various upgrades to preserve the current detector capabilities in the HL-LHC phase.

A broad outline of the scheduled ATLAS detector upgrades will be given in section 7.1. The remainder of this chapter focusses on research undertaken for one of these detector upgrades, namely the upgrade of the existing inner detector. This specific upgrade is described in detail in section 7.2. Section 7.3 and section 7.4 details the validation studies, followed by the main results and discussion. Section 7.5 summarises the main conclusions, and the current status of the detector construction in the lead up to the first HL-LHC collision.

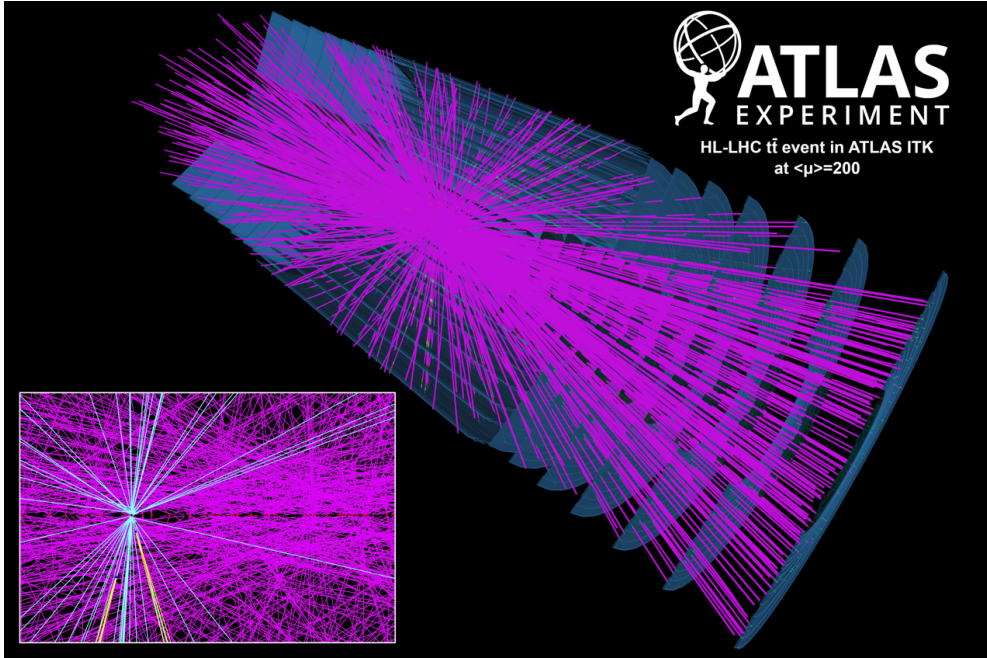


Figure 7.1: A simulated $t\bar{t}$ event in the ITk at the HL-LHC [125]. The average number of interactions per bunch crossing is assumed to be $\langle\mu\rangle = 200$. Each magenta line represents the trajectory of a particle, which all have transverse momentum larger than 1 GeV. The bottom left insert shows a zoomed in view of the interaction region. The tracks coloured in cyan represent those coming directly from the $t\bar{t}$ event. The tracks shown in yellow indicated those coming from the two secondary vertices. The interesting event in this example is $t\bar{t}$, hence all the magenta lines are considered as background.

7.1 Planned ATLAS detector upgrades for the HL-LHC

Many components of the existing ATLAS detector either require improvements or complete replacement, with a minimum goal of maintaining their performance over the HL-LHC lifetime given

the harsher experimental conditions expected. The diagram displayed in Figure 7.2 identifies the main components of the ATLAS detector which will undergo some form of upgrade in preparation for the HL-LHC runs. These include a brand new High-Granularity Timing Detector (HGTD) in the forward regions ($2.4 < \eta < 4.0$) of the detector which will be used as a way to separate collisions which occur very close together in space, but are well-separated in time [126], to mitigate the effects of pileup. Many sub-detector systems, including the Tile Calorimeter [127], Muon Spectrometer [128] and the liquid-argon calorimeter [129], will require new read-out electronics to be able to cope with the higher readout rates. The data acquisition system [130] will consist of a two-level trigger architecture: the level-0 (L0) trigger, plus the high level trigger (HLT) whereby the L0 trigger rate will be increased from 100 kHz to 1 MHz. A new Front-End LInk eXchange (FELIX) detector read-out system, currently being used only to read-out the trigger data for the Liquid-Argon Calorimeter, will be implement as the read-out system for all sub-detectors, receiving information from both the detector electronics as well as the L0 trigger.

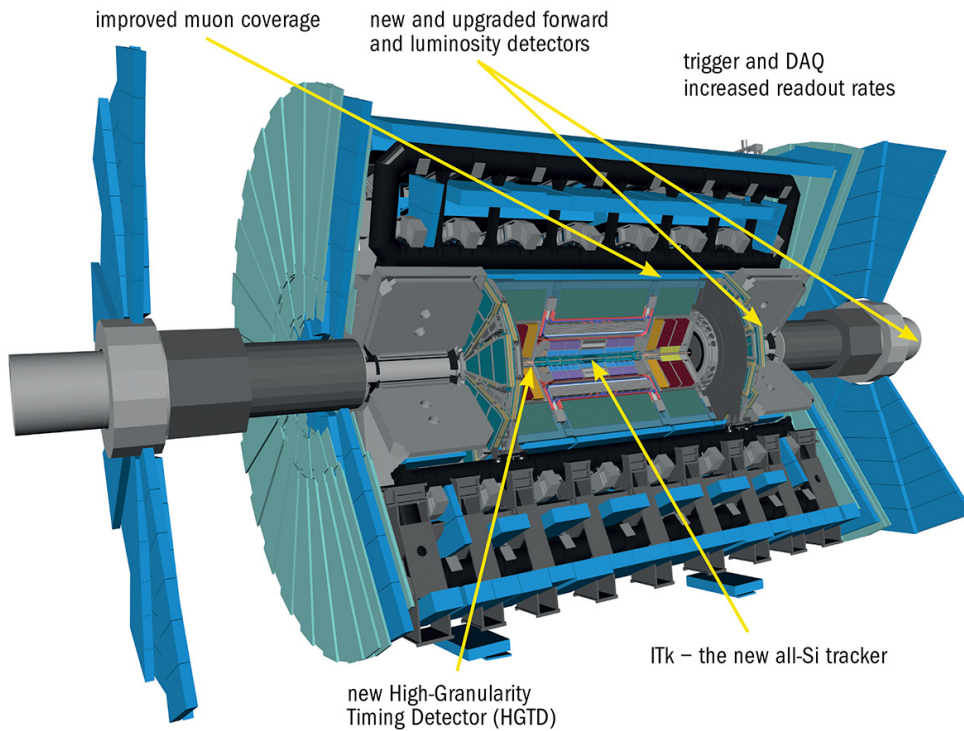


Figure 7.2: Main upgrades anticipated for the ATLAS detector in preparation for the HL-LHC [131].

One ATLAS sub-detector that needs to be entirely replaced is the existing inner detector. The detectors in general, but specifically the TRT is approaching 100% detector occupancy with the current pile-up values. Additionally, the existing inner detector uses radiation-hard sensors which were designed to maintain performance up to an integrated luminosity of around 800 fb^{-1} at most. These inner detector sensors are not suitable for operation past this limit. At pileup values

larger than $\langle\mu\rangle = 70$ most of the inner strip barrel layers cannot be read-out anymore due to bandwidth saturation; another limiting factor. Continuing to use the current inner detector during the HL-LHC runs would significantly limit the detector capabilities, thus substantially limiting the physics potential of the HL-LHC programme. As such, the inner detector will be replaced with a new all-silicon Inner TracKer (ITk) consisting of a silicon pixel detector and a silicon strip detector [132]. The ITk is designed specifically to obtain particle tracking information despite the high-radiation environment and large number of interactions per bunch crossing. Specific details of the ITk design will be given in section 7.2.

7.2 The Inner Tracker

The ITk is a new all-silicon tracker system comprised of pixel and strip sensor layers, each with a central *barrel* region and two *end-cap* regions. The terms pixel and strip refer to the type of silicon sensor that is used. This new tracker will replace the existing inner detector system which comprises of silicon pixel and strip sensor layers, as well as a transition radiation gaseous detector. In this way, silicon detector technology is being used out to a larger radius away from the interaction point compared to the existing inner detector, thus increasing the granularity out to that radius. This design choice results in more pixel and strip layers in both the barrel and end-cap regions compared to the corresponding current inner detector sub-components. A cross-sectional one quadrant view of the ITk design is shown in Figure 7.3. The blue (red) lines represent the strip (pixel) sensor layers respectively.

The overall aim of the ITk is to deliver equal or improved tracking performance compared to the existing inner detector. Meeting this requirement at the HL-LHC requires purpose-built sensor devices that are able to cope with the extreme operating conditions. The main design highlights for the ITk compared to the existing inner detector include:

- A factor 10 more channels in both the pixel and strip detector sub-components.
- Radiation hardness of detector components such that they have a lifetime of more than ten years. The radiation level is projected to exceed $2 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ in the innermost pixel layers. The unit $\text{n}_{eq}/\text{cm}^2$ measures radiation as an equivalent dose of 1 MeV-neutrons per cm^2 of material.
- The strip sensors are n-in-p type, compared to the p-in-n type used in the existing ATLAS SCT. Sensors of n-in-p type have an intrinsically higher radiation tolerance due to impact of radiation damage in the silicon bulk. This damage causes type-inversion of the bulk material to take place, where the p-bulk becomes p^+ , compared to n-bulk which would become p -type. Due to this, the n-in-p type sensors will have a significantly stronger signal after irradiation, compared to an equivalent p-in-n type sensor.
- Increased granularity for fast read-out electronics to cope with the higher pileup expected.

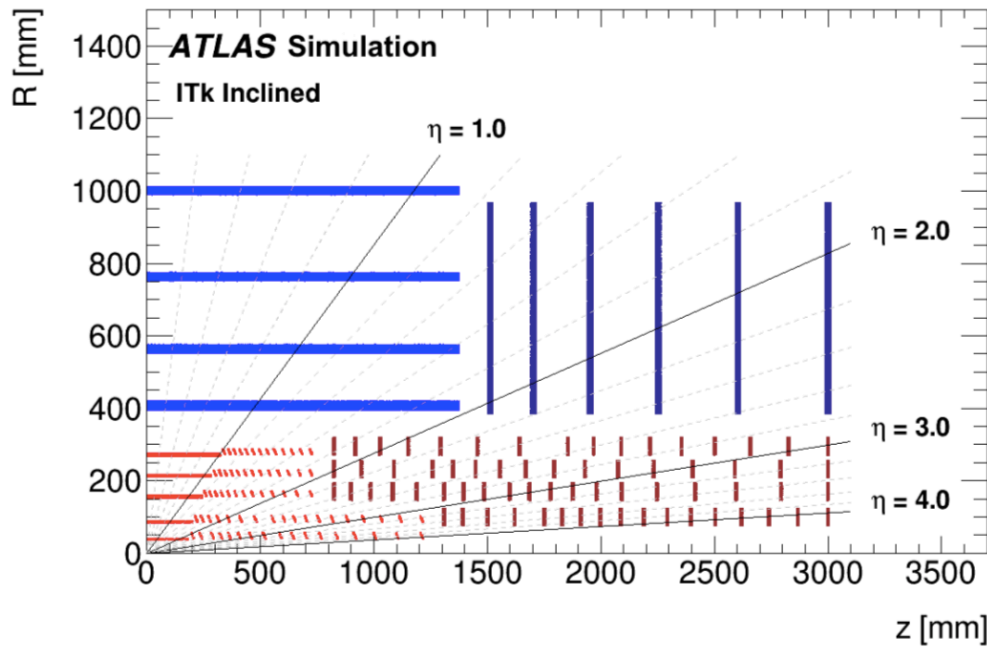


Figure 7.3: Technical diagram of the ITk layout for the HL-LHC ATLAS detector upgrade [132]. The light red lines represent the layers of the pixel detector in the barrel region, whilst the dark red lines correspond to the pixel components in the end-cap region. The light blue horizontal lines indicate the position of the strip detector layers in the barrel region, whilst the dark blue vertical lines correspond to the six disks of the strip detector in the one end-cap region. The interaction point, where the protons collide, is located at the origin. Only one quadrant of the ITk is shown, with the horizontal axis representing the beam line. The vertical axis represents the radius, in millimetres, out from the interaction point.

- Reduced material budget compared to the existing detector: the ITk strip components consist of $\sim 30 - 40\%$ less material by choosing to use a single-sided sensor. This means only one side of the sensors contains strips and the necessary protective coatings. Two sensors are then placed back-to-back, with a stereo angle between them, to obtain two dimensional information about the particles trajectory as it passes through the sensors.
- Extended η coverage out to $|\eta| < 4.0$ as shown in Figure 7.3, compared to the existing inner detector limit of $|\eta| < 2.47$. This extended range allows for the detection of particles in the very forward regions of the detector, and thus providing tracking information for particles in a much larger range than previously possible.

7.2.1 The ITk strip detector

The strip component of the ITk broadly speaking can be split into three main structural components: the sensor modules, the local support structure, and the global support structure. An overview of these structural components is displayed in Figure 7.4, where the left-most image is a cross-sectional view of the strip component of the ITk, the centre diagram shows one of the two

end-cap global structures as well as how the local support structures are mounted into the global support structure, and the right-most images shows a more close-up view of the local support structures, which is what holds in place the silicon sensor modules.

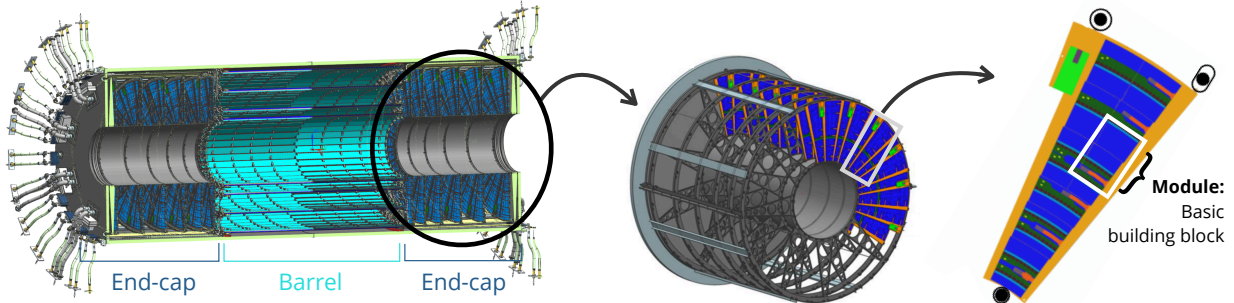


Figure 7.4: Diagrams showing the three main structural components of the ITk strip detector: the global support structure, the local support structure, and the sensor modules. The leftmost diagram displays a cross-sectional view of the entire ITk strip detector, highlighting the two main geometrical regions: the *barrel* is the central cylindrical region parallel to the beam axis, while the two *end-caps* are at either ends of the barrel. The central image depicts the end-cap global support structure in grey, which has been partially filled with the local support structures shown in blue. The right-most image is an enlarged view of the local support structure, known as petals in the end-cap region, which houses the individual sensor modules. These modules contain one silicon strip sensor, plus the necessary read-out electronics. Diagrams adapted from [132].

The smallest building block of the strip component of the ITk is the silicon strip sensor module. These modules consist of one single-sided silicon micro-strip sensor, as well as the necessary read-out electronics required to read-out the hits recorded by each individual strip. A cartoon diagram of one of the sensor modules is shown in Figure 7.5. The strip sensor used in the barrel region is square and has dimensions $97.54 \times 97.54 \text{ mm}^2$.

The local support structure in the end-cap region is known as a petal, since its shape resembles the petals of a flower. The centre diagram of Figure 7.4 illustrates how the petals are placed within the global structure, noting here that only three petals have been mounted in each of the rings as an example, but in practise they will cover the full 360° . Petals are mounted either side of each ring in the structure, with a stereo angle between them to ensure tracking information in all spatial directions can be measured for the particle tracks. Each petal is fixed to the global structure rings via three so-called *locking points*, illustrated as the three black circles in each corner of the petal as shown in the diagram on the right hand side of Figure 7.4. Each of these three locking mechanisms are designed with slight variations in their allowed kinematic movement such that they hold the petal to the global structure, whilst also not imparting any excessive force to the silicon sensors themselves which may be detrimental to the structural integrity of the sensor, or cause misalignment of the structural components. The three flavours of locking points are: one 4 mm diameter hole at $R \sim 375 \text{ mm}$, one 4 mm diameter slot at $R \sim 968 \text{ mm}$, and one 6 mm diameter hole at $R \sim 968 \text{ mm}$, where R indicates the radius out from the interaction point [132]. These specific holes or slot constrain the petals movement in the xyz , $z\phi$, and z planes respectively,

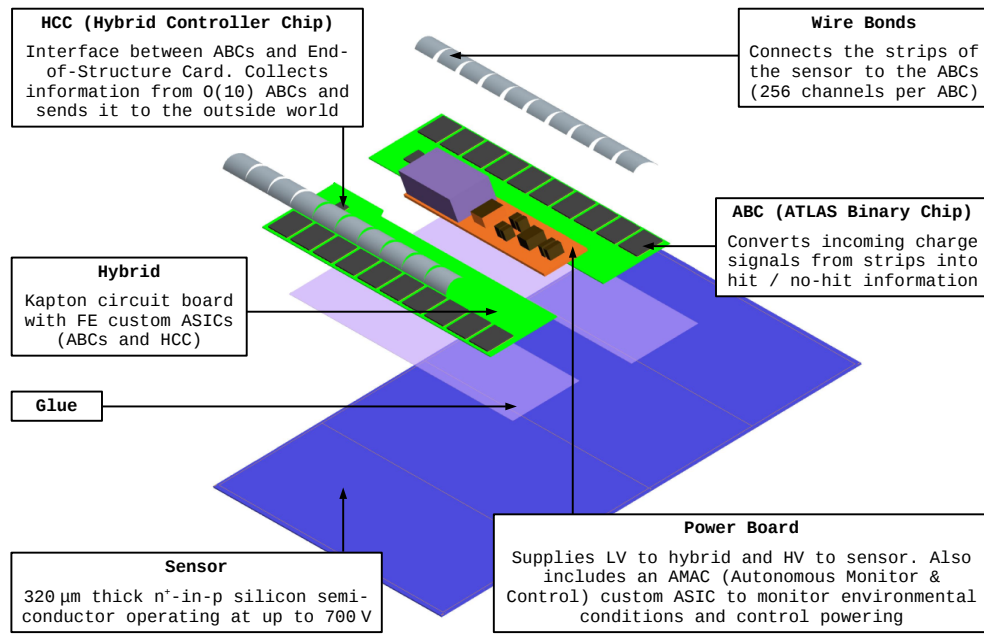


Figure 7.5: Labelled diagram of the strip sensor modules for the ITk. The particular sensor shown is for the barrel region, as it is square in shape and has dimensions $97.54 \times 97.54 \text{ mm}^2$. The key electronic components are labelled, and are glued on top of the sensor. The power board delivers the low voltage (LV) power supply to the hybrid, and high voltage (HV) to the sensor. The ATLAS Binary Chip (ABC) converts the charge signals recorded by the strips into hit/no-hit information. Diagram taken from [133].

where the z axis is the beam axis.

Individual sensor modules are mounted into the petals, where one petal houses 18 individual modules of various sizes, as shown in Figure 7.6. In addition to the modules themselves, the electronics required to interface with each module, as well as a CO₂ cooling system required to cool down the modules during detector operations, are also part of each petal. The location of the cooling pipe can be seen in the bottom diagram in Figure 7.6.

Section 7.2.2 described the global support structure of the strip component of the ITk in more detail.

7.2.2 The ITk end-cap global support structure

A diagram of the global support structure, in the end-cap region, is shown in Figure 7.7; the structure is comprised of six rings, one stiffening disk, and an inner cylinder all wound from carbon fibre filaments and epoxy. The left hand side shows the individual components separately, whilst the right hand side is fully assembled.

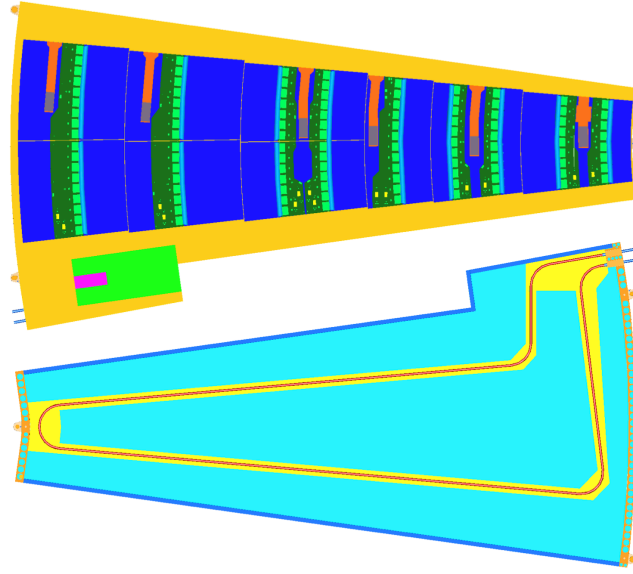


Figure 7.6: Diagrams depicting the local support structure for the strip component of the ITk, known as petals in the end-cap region. The top diagram shows in blue how the modules are arranged on the petal, including in green the individual read-out electronics. The bottom diagram shows the internal CO₂ cooling system for one petal, where the CO₂ is circulated through the pipe drawn in red [132].

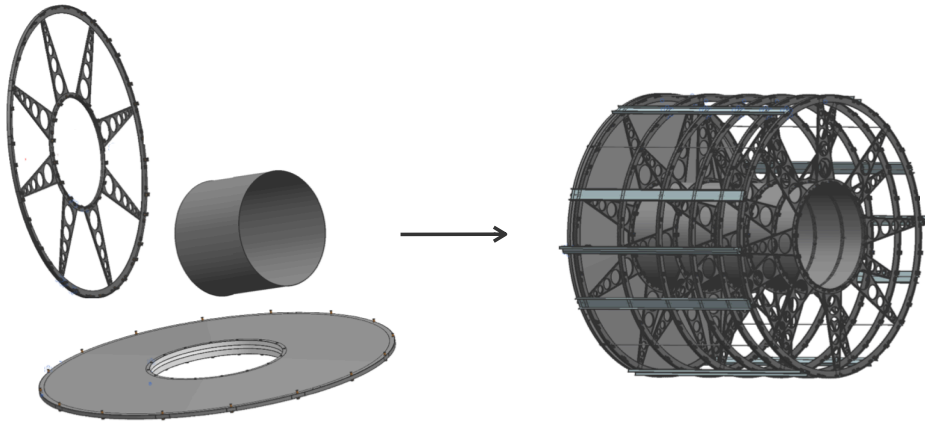


Figure 7.7: Diagrams depicting the end-cap global structure for the strip component of the ITk. The left image shows the three main components of the global structure: the rings, the inner cylinder, and the stiffening disk. Each end-cap consist of six rings, one inner cylinder, and one stiffening disk. The right diagram shows the structural components fully assembled [132].

Nikhef - the Dutch National Institute for Subatomic Physics - is responsible for manufacturing the global structure for the two ITk strip end-caps. Details of the ITk and the research presented in this thesis consequently have a strong focus on the global structure for the ITk strip end-caps. Any mention of the global structure for the rest of this thesis refers specifically to the global structure in the end-cap region for the strip component of the ITk. The rings of the global structure hold

in place the petals, and must absorb any mechanical stresses which could affect the petal, and in particular the silicon sensors they support. The stresses typically derive from either variations in environmental conditions, for example temperature and humidity fluctuations, or from external vibrations during detector operations. The locking points used to kinematically fix the petals to the global structure, will allow for some of this mechanical stress to be redistributed though only up to a certain threshold. It has been noted in Chapter 10 of the Technical Design Report [132] what the allowed upper limit is for each individual component of the global structure to be considered safe and not affect the petal alignment, structural integrity, and thus performance. In the case of the individual rings, each ring must deform no more than roughly $100\text{ }\mu\text{m}$ over a temperature range of -30°C to $+20^\circ\text{C}$. This requirement is stated in equation 7.1, where Δx denotes the displacement in the specific direction of interest.

$$|\Delta x|_{-30^\circ\text{C} \rightarrow +20^\circ\text{C}} \leq \sim 100\text{ }\mu\text{m per ring} \quad (7.1)$$

During detector operations, the temperature should be stable around -30°C . The quoted required temperature range for qualification is derived from taking the structure from room temperature down to the expected operational temperature. This means understanding the behaviour of the structure as the temperature is changing, and not simply just at the extremities is also important. Due to the directional carbon fibre winding, the structure is wound stiff in the plane along the rings, meaning the plane perpendicular to the beam (z) axis. Consequently, the direction more prone to deforming is perpendicular to the stiff direction. This corresponds to movement between the rings themselves. To verify if the end-cap rings meet the specification, a *cooling test* will be performed, whereby the measurement system employed will track in real time how the rings deform as the temperature changes. The research presented in this chapter aims to verify if this design specification is satisfied.

7.2.3 A mock-up of the end-cap global structure

One of the first steps in the fabrication of the end-cap global structures is to build a mock-up of the end-cap design for testing purposes. The mock-up consists only of the two innermost rings (ring 0 and ring 1), the inner cylinder, and the stiffening disk. A diagram labelled with these components is shown in Figure 7.8.

This mock-up was built for two main reasons. Firstly, for the involved engineers to practise the carbon fibre winding procedure required to make the final two global structures. Additionally the mock-up is used to take preliminary measurements of the structural properties in order to check for any obvious problems in the structural design, before moving on to fabricating the two structures that will actually be used for the ITk. To achieve this goal, suitable measurement systems and procedures must be developed, that can be used to validate the final two global

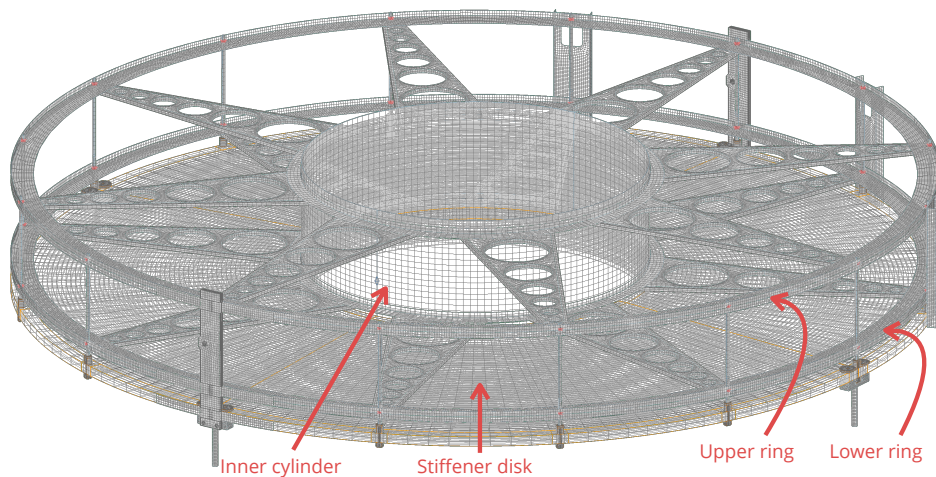


Figure 7.8: Technical drawing of the ITk strip end-cap global structure mock-up. The mock-up consists of the two innermost rings, one third of the inner cylinder, and the stiffening disk.

structures. This will be the subject of section 7.3, which includes the deformation measurement results undertaken on the mock-up structure.

7.3 Mechanical alignment of the ITk strip end-cap global structure mock-up

To quantify the thermally induced deformation of the end-cap global structure components, an alignment monitoring system is necessary to measure the deformation in real-time, as the environmental conditions are changing. A series of measurement systems have previously been assessed for their suitability, including calipers, strain gauges, lasers, and the Rasnik alignment system. The limiting factor in most of these cases was either one (or some combination) of the following reasons. The measurement system must be glued to the surface of the structure, which is acceptable for testing a mock-up, but not the final structures. The system was too inaccurate, for example $100\text{ }\mu\text{m}$ accuracy in the case of the calipers. The complexity of the structure made it difficult to attach the measurement device to the structure in a way which allowed for meaningful results to be extracted.

In addition to taking real-time measurements, it is also possible to simulate the structure's behaviour via a Finite Element Analysis (FEA). The components of the global structure are quite compositionally complex, which renders any simulation of the mechanical behaviour difficult and often inaccurate. For example, the structure used to attach the individual LVDT components to the mock-up have a uni-directional carbon fibre inner layer, and a weave pattern in the outer layer. Such complexity makes it very difficult to predict the response of the material to changing temperature, quantified as the *coefficient of thermal expansion*. Simulating the global structure using a FEA requires as inputs the coefficient of thermal expansion for each individual component to be

accurate, hence any simulation of this type will carry a large uncertainty. This further emphasises the need for a real-time measurement system.

Due to the lack of an adequate, fit-for-purpose displacement measuring system, an alternative must be devised. Linear Variable Differential Transformers (LVDT) are the proposed alignment monitoring system, and the topic of investigation presented in the following sections of this chapter. LVDTs accurately measure displacement in one-direction, where in this context, *accurately* is defined as the ability to measure displacement with an uncertainty of $\lesssim 10\ \mu\text{m}$, and be well-behaved in the desired measurement temperature range. This target is chosen to be roughly one order of magnitude lower than the specification such that the measurement results are conclusive enough to ascertain if the outlined specification is met. To assess the feasibility of using the LVDT system, a series of validation and *proof of principle* tests are undertaken to identify if this system can be adapted in a way that is suitable for the desired measurements, as well as reaching the target precision. Details pertaining to these tests, and the LVDTs in general are presented in this section. Following the success of these tests, LVDTs have subsequently been used to measure deformation of the global structure components, specifically the stiffening disk, during the fabrication and assembly phase at Nikhef.

An introduction to the LVDT components, and how the system works will be described in section 7.3.1, where the initial precision estimate and the calibration studies are also detailed. Section 7.3.5 outlines how and where the LVDTs are attached to the mock-up structure. Section 7.3.7 presents the measurement results when using the LVDTs to measure thermally induced deformations. Deformation measurements of the three fabricated stiffening disks, using the LVDT system, are presented in section 7.4, along with a discussion of the observed results.

7.3.1 Introduction to LVDTs

LVDTs are an electrical system designed to measure displacement, Δx , in one direction. The key components are a primary coil with a graphite core, and two secondary coils. Current flowing in the primary coil generates a magnetic field in the graphite core, which in turn induces a current through the secondary coils. The primary coil is free to move in and out of the secondary coils; a small displacement of the primary coil causes a greater current induced in one of the secondary coils. This difference is measured with a voltmeter as a change in voltage, ΔV , and can be precisely converted to a displacement once calibrated. Section 7.3.3 will describe the calibration process. A key feature of the LVDT design is that the secondary coils are wound in opposite directions such that directional information can be extracted from the current induced in the secondary coils. The coils consist of copper wiring, wound around purpose-built frames. These frames and the coil windings are handmade on site in the engineering department at Nikhef. An image of the primary and secondary coils are shown in Figure 7.9.

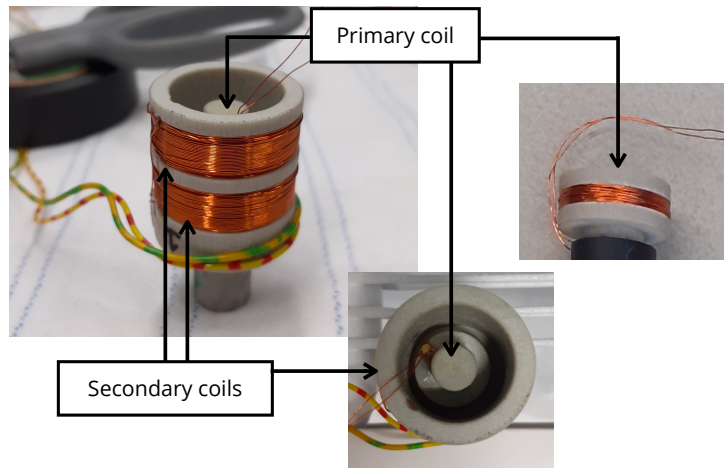


Figure 7.9: Images showing the LVDT system, which is comprised of the primary and secondary coils.

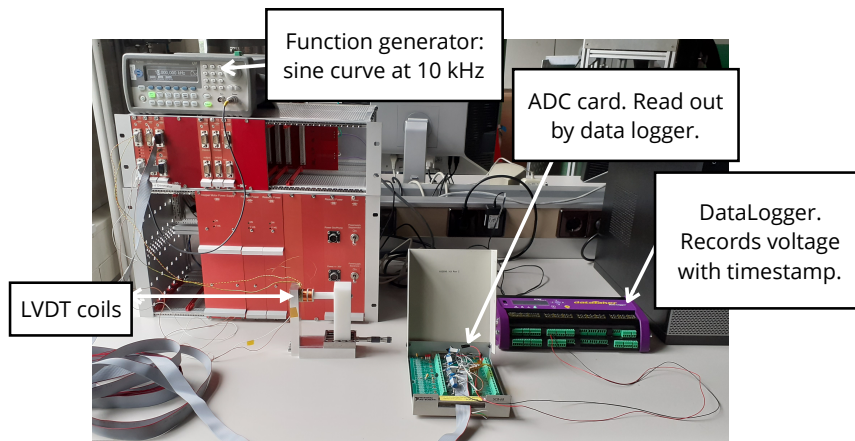


Figure 7.10: Photograph of the test set-up of the LVDT system used to quantify the inherent noise of the set-up, and to take calibration measurements used to accurately convert the voltage reading to the corresponding displacement value. Included in the image is the DataLogger data recording device, used to take time-stamped voltage readings at user-defined time interval. The function generator used to deliver the current to the primary coils is also shown.

The data acquisition system is shown in Figure 7.10. This set-up consists of a function generator which delivers a high-frequency sine curve signal at 10 kHz to the primary coils. The measured signal from the secondary coils is passed through a signal processing card which filters out everything above 40 Hz. The remaining signal is then passed to the ADC card which converts the analog signal to a digital one, through an RC (resistor–capacitor) filter. The ADC card is wired to a DataLogger which is able to take time-stamped voltage measurements every second.

Prior to the LVDT system being used as an alignment monitoring system, an understanding of the inherent noise of the set-up is studied and detailed in section 7.3.2.

7.3.2 Accuracy of the LVDT system

A test set-up is used to take the noise measurements of the coils, as well as being used to calibrate the system. This is shown in Figure 7.11 and consists of an aluminum and a glass epoxy support frame bolted together so the primary and secondary coils remain in a fixed position with respect to each other. The smallest division on the micrometre was $20\text{ }\mu\text{m}$. Assuming a uniform distribution of values between each division, the uncertainty on each individual position measurement is thus $20/\sqrt{12} = 5.8\text{ }\mu\text{m}$.

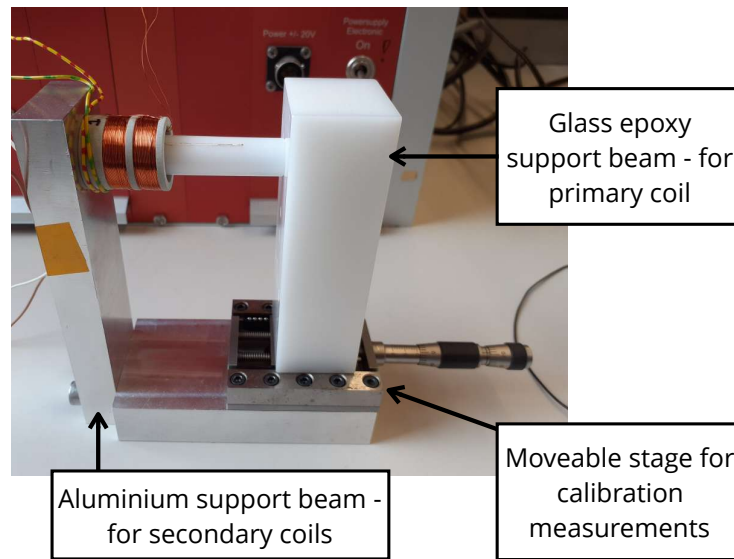


Figure 7.11: The test set-up used for preliminary noise and calibration measurements of the LVDT system. The support beams are bolted together such that the primary and secondary coils are unable to move with respect to each other. The glass epoxy frame supporting the primary coil is mounted on a manually moveable stage, which is used to calibrate the system (described in section 7.3.3).

Measurements of the inherent noise is taken with the test set-up, to provide an estimate of the system's accuracy. This involves taking a series of voltage readings at period time intervals, whilst the coils are not moving. The resulting voltage distribution is expected to be roughly Gaussian in shape, where the spread of points provides an estimate of the accuracy. The noise measurement results are shown in Figure 7.12, where the distribution is fitted with a Gaussian function. The spread of the distribution, given by the width of the Gaussian peak, is 4.3 mV . Given the LVDT system works by converting a difference in two voltage points, ΔV , the uncertainty of interest is thus on the difference between two voltage measurements, so $\sqrt{4.3^2 + 4.3^2} = 6.1\text{ mV}$. It should be noted that the measurements taken thus far use the calibration set-up which is designed such that the primary and secondary coils can't move with respect to each other.

Figure 7.13 shows the measured voltage values when the primary coil is moved slightly in (shown in orange) and out (shown in purple) of the secondary coils. Note that the absolute value of the

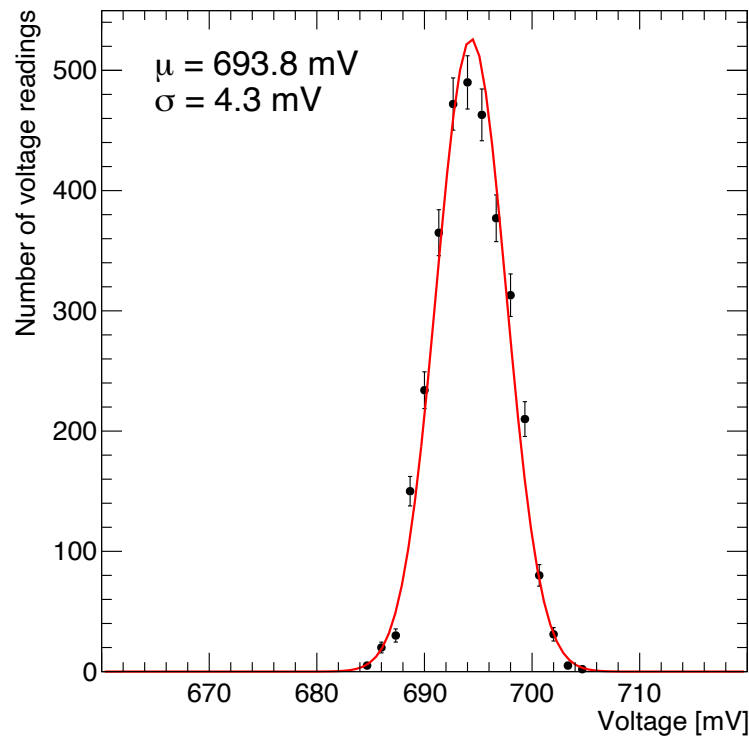


Figure 7.12: Noise measurements of the LVDT calibration set-up. The spread of the data points, obtained by fitting a Gaussian distribution to the data, suggests the statistical uncertainty on each voltage measurement is 4.3 mV. The absolute value of the voltage is arbitrary since the parameter of interest is ΔV . In total, 3420 voltage readings were recorded to obtain this histogram.

voltage recorded is not important. Rather it is the change in voltage that corresponds to the displacement, Δx . For the results shown in Figure 7.13, it is clear from the y-axis that $\Delta V \approx 120$ mV. This can be precisely converted to a Δx (once the system is calibrated), using the conversion factor obtained from the calibration measurements. The exact voltage values corresponding to the start and end positions for each of the three trials is reported in Table 7.1. Measurements in

Direction	Trial number	Start voltage [V]	End voltage [V]
In	1	444.0	559.4
In	2	447.6	566.6
In	3	446.8	562.0
Out	1	565.4	446.9
Out	2	566.3	448.0
Out	3	562.1	443.4

Table 7.1: Measured voltages recorded at the start and end positions of the primary coil movement. The *direction* of movement indicates whether the primary coil was displaced *into* or *out* of the secondary coil. The uncertainty on each voltage value is ± 4.3 mV. Each of the start and end positions are consistent among each of the three repetitions, as well as among the two coil movement directions.

two directions have been performed, to check for consistency among both directions. *In* refers

to the primary coil being moved further in the secondary coil; *out* is the reverse direction. Good consistency is seen among the three trials; the start and end values are statistically compatible in all cases. The measurement points between time $\sim t = 40$ s and $t = 80$ s seem to fluctuate quite a lot. This is due to the manual nature of the moveable stage and is not a cause for concern, since the source of the behaviour is understood.

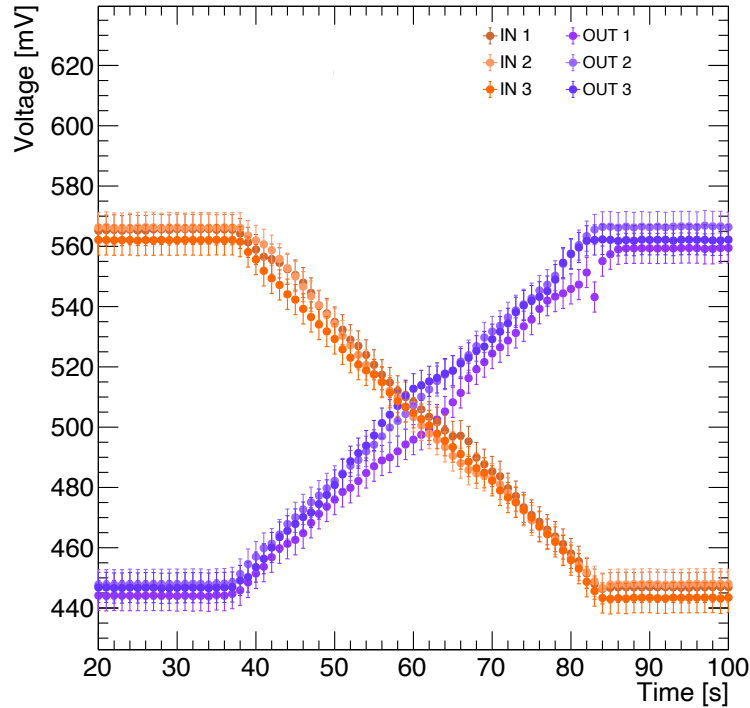


Figure 7.13: An example of the LVDT coil behaviour due to manually movement of the primary coil in (shown in orange) and out (shown in purple) of the secondary coils. This test was repeated three times per direction to check for consistency among repeated measurements, which is observed. The statistical uncertainty of 4.3 mV on each voltage point, as obtained through noise measurements, is included.

7.3.3 Calibration of the LVDT coils

A set of LVDT coils must be calibrated to obtain the correct voltage (ΔV) to displacement (Δx) conversion factor. The success of the LVDT system is defined by how accurately the ΔV measurements can be converted to a displacement value, Δx . A moveable micrometre stage is used in the calibration set-up, to allow for voltage measurements to be taken at known positions, x . It is expected that the voltage recorded is linearly dependent on the position of the coils. Therefore, once such measurements are made, the gradient of the fitted line is the conversion factor allowing for ΔV values to be converted to a displacement, Δx . A *calibration run* consists of voltage readings being taken at 100 μm intervals, in the range $-1600 \rightarrow 1600 \mu\text{m}$, the results of which are shown in Figure 7.14.

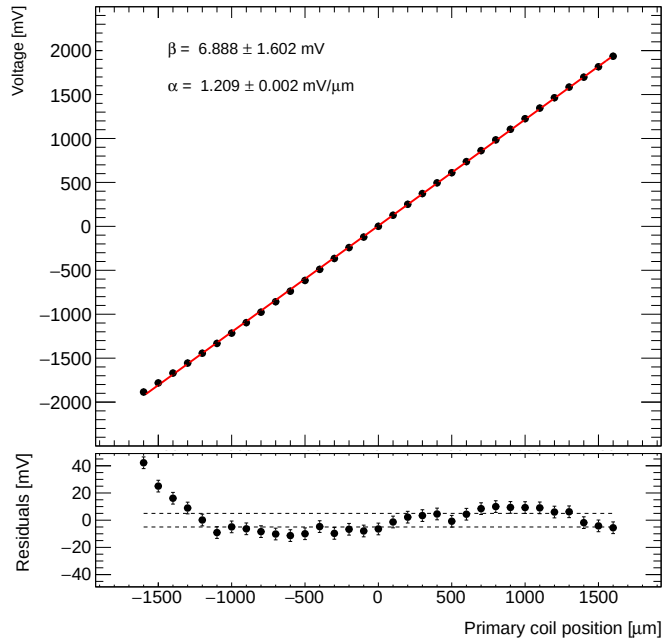


Figure 7.14: Calibration of the LVDT system: the top plot shows the measured voltage as a function of the micrometre position, which represents the displacement of the primary coil. The data are then parametrised with a linear function, where the gradient (α) and intercept (β) values are determined by the best fit value. The gradient of this linear function represents the conversion factor between a ΔV measurement, and the corresponding displacement, Δx , for this specific LVDT set. The lower insert plot displays the residuals between the data points and the line of best fit. The uncertainty on the primary coil position, coming from the precision of the micrometre, is $5.8 \mu\text{m}$. The statistical uncertainty on the measured voltage points is 4.3 mV .

As can be seen in Figure 7.14, the expected linear behaviour is observed, and the points were fitted with a linear function, $f(x) = \alpha \cdot x + \beta$. The residuals are plotted in the bottom panel of Figure 7.14, where the dotted lines indicate the $\pm 1\sigma$ uncertainty bands. It's worth noting that the nominal measurement range of the LVDTs is around $\pm 1 \text{ mm}$; this is where the magnetic field is most uniform. Extending beyond this range can result in non-linear effects when trying to convert between voltage and displacement. This is particularly evident in the region where the primary coil position is around $-1500 \mu\text{m}$.

Each voltage measurement recorded was ascribed an uncertainty of 4.3 mV aligned with the accuracy estimate determined by the noise measurements presented in section 7.3.2. This means the uncertainty on ΔV is 6.1 mV . The uncertainty on the position values was taken to be $5.8 \mu\text{m}$. The conversion factor obtained is the fit value of the gradient: $1.209 \pm 0.002 \text{ mV } \mu\text{m}^{-1}$. This calibration run was repeated two more times to check for consistency among repetitions, and the three gradient values obtained are shown in Table 7.3.3.

Calibration run	Gradient (α , from fit)
1	1.209 ± 0.002
2	1.206 ± 0.006
3	1.207 ± 0.004

Table 7.2: Gradient, α , values obtained from a linear fit to the voltage versus position measurements during the three calibration runs taken of the LVDT set-up.

From the three fit values obtained, an average was taken to obtain a conversion factor:

$$\Delta V = (1.207 \pm 0.007) \cdot \Delta x \quad (7.2)$$

As per the noise measurements discussed in section 7.3.2, the uncertainty on ΔV obtained results in a displacement accuracy of $5.1 \mu\text{m}$, using the conversion factor of equation 7.2. This is well within the desired order of magnitude of $\lesssim 10 \mu\text{m}$, and indicates the LVDT system is well poised to conduct deformation measurements on the global structure mock-up.

7.3.4 Systematic uncertainties

Aside from the statistical uncertainty associated with each voltage measurement, systematic uncertainties of the LVDT system must also be evaluated. In particular, the following three potential sources of systematic uncertainties were investigated to further understand the behaviour of the LVDT system across the temperature range required.

1. Thermal stability of LVDT coils:

The first study intends to investigate the effects of temperature on the coils themselves; to understand if, when operated across a temperature range of -20 to $+20^\circ\text{C}$ (as expected during the cooling test) the voltage measurements were stable, or if some unexpected thermal effects were present. To ensure only the thermal effects on the coils were tested, the calibration set-up was used such that the two coils were held at a fixed position. Initially the primary coil was located at a micrometre position of $-400 \mu\text{m}$, which is within the central region of the coil measurement range. The thermal stability test then proceeded as follows. The starting temperature was $+20^\circ\text{C}$, where for reference a series of initial voltage measurements were taken. The set-up was then placed inside a freezer where the ambient temperature fluctuated between -19°C and -23°C . Once the temperature of the coils reached equilibrium with the ambient temperature, the voltage readings stabilised, as is shown by the pink curve in Figure 7.15b. Since stability is observed, it can be concluded that no unexpected thermal effects are seen across the defined temperature range.

To confirm this result is also true near the edge of the LVDT coil measurement range, the thermal stability test was repeated placing the coils at a micrometre position of $-1000 \mu\text{m}$. These results are shown by the green measurement points in Figure 7.15b, where again for reference a series

of voltage readings were taken at +20deg, before placing the coils in the freezer. No unexpected thermal effects were evident, the voltage readings stabilised after around 30 minutes and thus no additional systematic uncertainty is required.

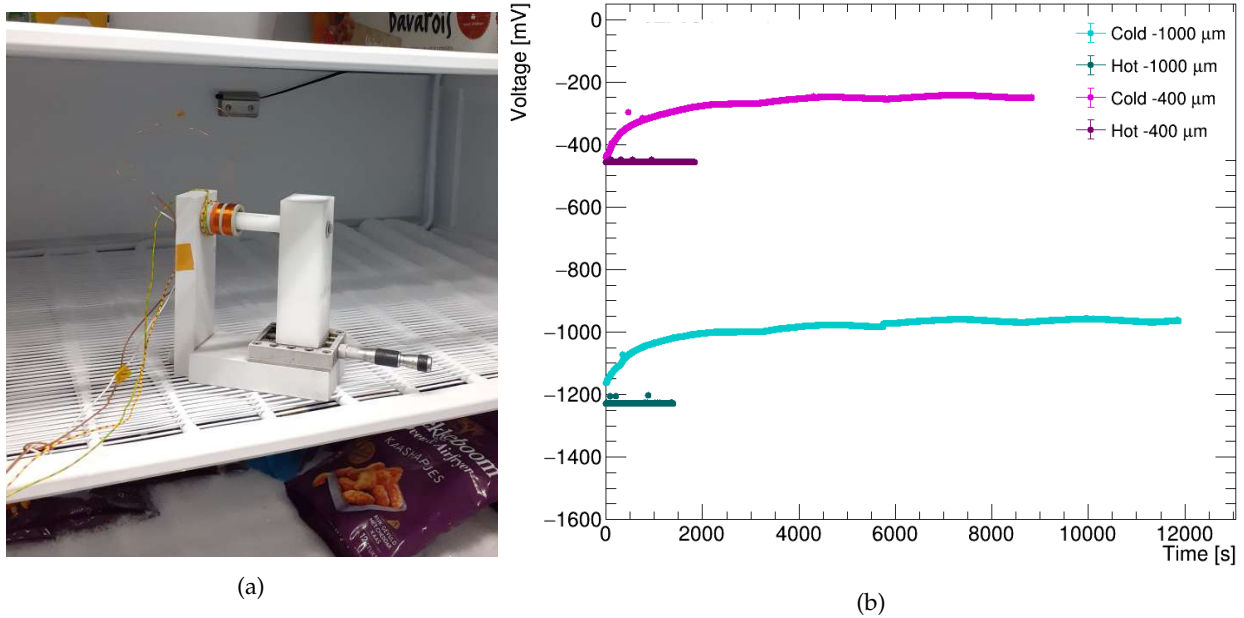


Figure 7.15: LVDT coil thermal stability test set-up and measurement results. Figure 7.15a shows an image of the set-up once placed in the freezer. The results are shown in Figure 7.15b, where the darker colours correspond to measurements taken outside the freezer at +20°C, and the lighter colours are the voltage readings taken once the set-up was placed inside the freezer at $\sim -19^{\circ}\text{C}$ to -23°C . Note that as the LVDT system measures relative displacement, the absolute value of the voltage is irrelevant. Two fixed positions of the primary and secondary coils were tested: $-400\text{ }\mu\text{m}$ shown in pink, and $-1000\text{ }\mu\text{m}$ shown in green.

The difference in voltage between the respective hot, and cold, plateaus is expected and is solely due to the temperature response of the coil and set-up structure. This will be accounted for in section 7.3.5.

2. Hysteresis effects:

Another possible source of systematic uncertainty could be if the rings didn't return to their original position after being deformed, meaning there is evidence of hysteresis present. The effect due to hysteresis alone can be quantified by verifying if the rings return to their original position in a controlled environment, with no ΔT , and only one mechanical change happening to the rings. Such a test was undertaken by manually applying pressure to deform the upper ring for period of five seconds, then releasing. Voltage measurements were recorded throughout the duration of this test to check for signs of hysteresis, this is shown in Figure 7.16.

As seen in Figure 7.16 the starting voltage of the LVDT coils is $2756 \pm 2.6\text{ mV}$, a change of 631.3

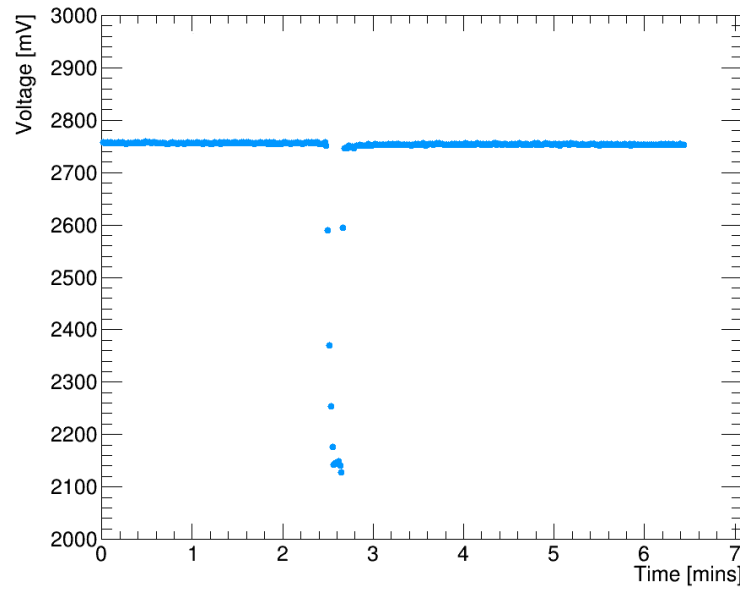


Figure 7.16: Voltage measurements recorded by the LVDT coils as a function of time during which, the upper ring was manually deformed for a period of five seconds, to check for evidence of hysteresis. The final position of the rings is measured to be statistically compatible with the original position, hence no hysteresis is observed.

± 3.6 mV is observed, and the ring returns to 2753 ± 2.6 mV. This change can be converted to a displacement of $523 \mu\text{m}$. The difference between the initial and final positions is $2.5 \mu\text{m}$, with a statistical accuracy on Δx of $3.6 \mu\text{m}$. Given the difference between start and final positions is within the uncertainty stated, the conclusion is that no hysteresis is seen. This test was repeated three times for confirmation of results, and in each case the structure returned to its original position.

3. Transverse coil movement:

The diameter of the primary coil is slightly less than the inner diameter of the secondary coil housing, shown in Figure 7.17a. This is to ensure the primary coil doesn't touch the walls of the secondary coil housing, and subsequently inhibits the free movement of the coils. This extra space potentially allows for the coils to move also in the plane perpendicular to the vertical direction. To first order, such sideways movement should result in no change in voltage, as the current induced in the secondary coils wouldn't register the movement. To investigate whether sideways movement was a source of systematic uncertainty, the calibration set-up, as per Figure 7.11, was re-assembled in such a way that allowed for sideways (left and right) movement by the micrometre stage, instead of the usual vertical-only movement. The primary coil was moved to the left and right of its central position to check for any deviations in the voltage readings. The results are displayed in Figure 7.17b.

A distinction is seen between the centred primary coil ($t = 0 - 2$ mins, $4.5 - 7$ mins, and $9 - 10.5$

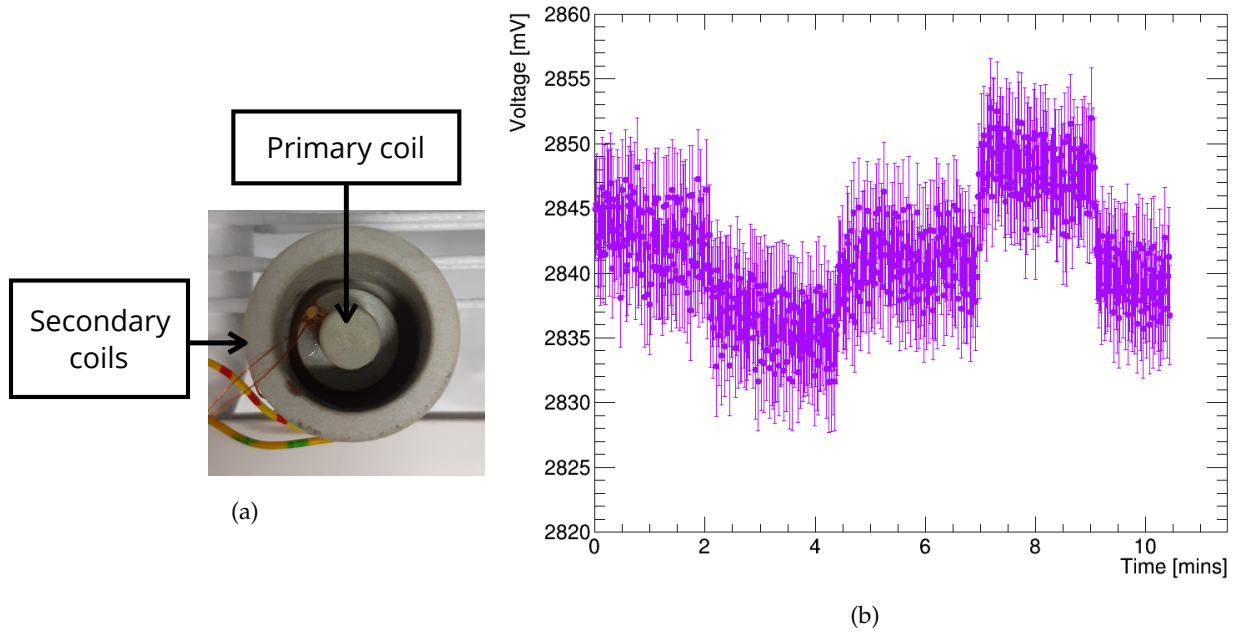


Figure 7.17: Figure 7.17a displays the LVDT coils where a clear view of the space between the primary coil and the secondary coil housing is captured. Figure 7.17b shows the voltage distribution as a function of elapsed time, during which the primary coil is moved left ($t = 2 - 4.5$ mins) and right ($t = 7 - 9$ mins) of the central position with respect to the secondary coil.

mins), when the coil is completely to the left ($t = 2 - 4.5$ mins), and when it's completely to the right ($t = 7 - 9$ mins). A visual difference is observed when the coils are moved to the left and right; there is a 5 mV difference between the mean voltage values of the primary coil located in the central position with respect to either the left or right position. Consequently, a $5 \text{ mV} \equiv 4.1 \mu\text{m}$ systematic uncertainty is applied. This is the maximum amount the primary coil could move inside the secondary coil housing, so there is no chance of any further transverse movement.

Combining all expected sources of systematic uncertainties presented in the sections above, the total uncertainty on a Δx measurement is $\pm 3.6 \mu\text{m}$ (stat.) $\pm 4.1 \mu\text{m}$ (sys.), which equates to a combined total of

$$\pm 5.5 \mu\text{m}. \quad (7.3)$$

This places the total accuracy of the three coil sets within the target range, thus confirming their suitability in conducting deformation measurements of the global structure mock-up.

7.3.5 Attaching the LVDTs to the mock-up

In order for the LVDTs to be used to measure the thermal deformation, an appropriate structure had to be developed, in collaboration with the mechanical engineers at Nikhef, to mount the LVDT system onto the global structure mock-up. This structure ideally would be constructed of materials with known coefficients of thermal expansion (CTE), such that their behaviour due

to changes in temperature could be correctly accounted for. Taking into account the layout of the mock-up, the LVDT supports would be designed in such a way that the relative deformation measured was between the upper and lower rings. Concretely, this means that the secondary coil would be attached to the lower ring, and the primary coil attached to the upper ring. The measured voltage from the LVDT system then quantified how much the upper and lower ring deformed with respect to each other, and in which direction (further apart or closer together). The coils must be mounted parallel to the plane of the rings to measure the ring deformation. Since the LVDTs measure displacement in one direction only, any sideways movement is a second order effect¹.

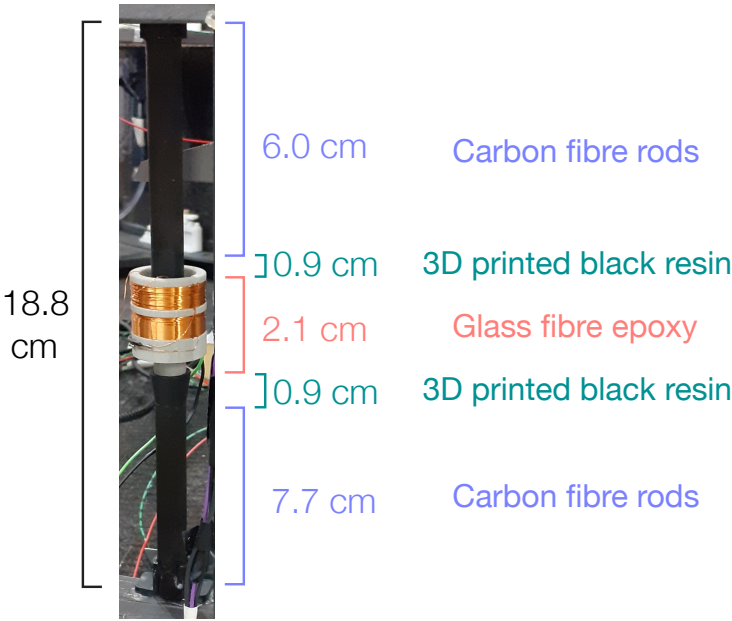


Figure 7.18: Dimensions and composition of the LVDT support structure components.

The mount (one each for the primary and secondary coil) consists of a uni-directional carbon fibre rod which attaches to the coil housing. Uni-directional indicates the fibres are woven in one direction only during the fabrication process, and the resulting structure is extremely stiff in that direction. Quantitatively, this means the CTE is roughly three times lower than if the fibres were woven at a 45° angle. One end of the rod is glued to a piece of 3D printed black resin, which fixes the rod to the glass epoxy coil housing. The other end of the rod attaches to the end-cap ring, and also has an extra piece of black resin attached to the exterior, which ensures the rod remains perpendicular to the plane of the rings. Figure 7.18 details the various compositions and dimensions of the LVDT supports. The CTE for each type of material used in the LVDTs and in building the supporting supports are given in Table 7.3. Across any given change in temperature,

¹To verify this, a so-called *transverse* test was conducted as part of the systematic studies. This is outlined under the sub-heading **Transverse coil movement** in section 7.3.4.

the materials used in the LVDT supports will themselves expand or contract, in addition to the thermal deformation of the global structure rings. The deformation of the LVDT supports will be calculated below such that this behaviour can be accounted for.

Material	CTE [per metre, per K]
Uni-directional carbon fibre	$\sim 1 \mu\text{m}$
3D printed black resin	$\sim 60 \mu\text{m}$
G10 FR4 glass fibre	$\sim 10 \mu\text{m}$

Table 7.3: Coefficient of thermal expansion (CTE) values for each material used in the LVDT supports. Each CTE value quoted corresponds to the change in length of that material, per metre used of that material, per degree change (in Kelvin). The exact value of the 3D printed resin is unknown but the best estimate (from the involved engineers) is to use that of peek, an organic thermoplastic polymer.

The other CTE values quoted were previously measured by the involved engineers.

All cooling tests undertaken on the mock-up start warm $\sim +20^\circ\text{C}$, and then the temperature drops once the dry-ice is circulated. The expectation is thus that all materials mentioned in Table 7.3 will shrink as the cooling test progresses. As a result, the primary and secondary coils will move apart from each other solely due to the change in temperature, and the measured voltage output will be a positive change. Using the length of each material used, from Figure 7.18, with the corresponding CTE values in Table 7.3, and a temperature change of $\Delta T \sim 50 \text{ K}$, the expected shrinkage of the supports can be calculated. The uncertainty on each measured component length is the inherent precision of the ruler used, 0.0014 m. The total uncertainty quoted is simply propagated from the individual length uncertainties.

Primary coil mount:

Carbon fibre rods:	$1 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.06 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 3 \mu\text{m}$
Black resin:	$60 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.009 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 27 \mu\text{m}$
Glass fibre:	$10 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.005 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 2.5 \mu\text{m}$

Total:	$= 32.5 \pm 2.4 \mu\text{m}$
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Secondary coil mount:

Carbon fibre rods:	$1 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.077 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 3.85 \mu\text{m}$
Black resin:	$60 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.009 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 27 \mu\text{m}$
Glass fibre:	$10 \mu\text{m m}^{-1} \text{K}^{-1} \times 0.021 \text{ m} \times (\Delta T = 50 \text{ K})$	$= 10.5 \mu\text{m}$

Total:	$= 41.4 \pm 2.4 \mu\text{m}$
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During the cooling test, the primary (secondary) coil mount will shrink by $32.5 \pm 2.4 \mu\text{m}$ ($41.4 \pm$

2.4 μm) respectively, thus the combined effect is that the LVDT coils will measure them moving apart from each other by $73.9 \pm 3.4 \mu\text{m}$, equivalent to $89.2 \pm 4.1 \text{ mV}$. Therefore the expected behaviour of the supports due to the change in temperature alone, is the appearance of the upper and lower rings moving apart from each other by $73.9 \pm 3.4 \mu\text{m}$. The result of this calculation will need to be accounted for when analysing the results of the cooling test (section 7.3.7).

7.3.6 Validation of the LVDT-measured displacement

Validation of the displacement measured by the LVDT system is required to confirm that the returned value corresponds to the true value the structure deformed by. A test was undertaken to confirm this whereby a dial gauge was used to measure the deformation at the same time as the LVDT coils. The dial gauge was positioned with the needle on the top surface of the upper ring of the global structure mock-up, directly above where the primary coil is mounted. The upper ring was manually pushed down and the resulting induced deformation was directly measured by the dial gauge, while the LVDT coils recorded the change in voltage as a function of time. The dial gauge measured a deformation of $-50 \pm 3 \mu\text{m}$. The results obtained from the LVDT coils are shown in Figure 7.19, where the relative displacement is shown directly. The displacement measured by the LVDTs is $-51.9 \pm 3.6 \mu\text{m}$. This indicates the LVDT and dial gauge measurements are compatible, and thus deformation recorded by the LVDTs does correspond to the actual deformation of the mock-up structure.

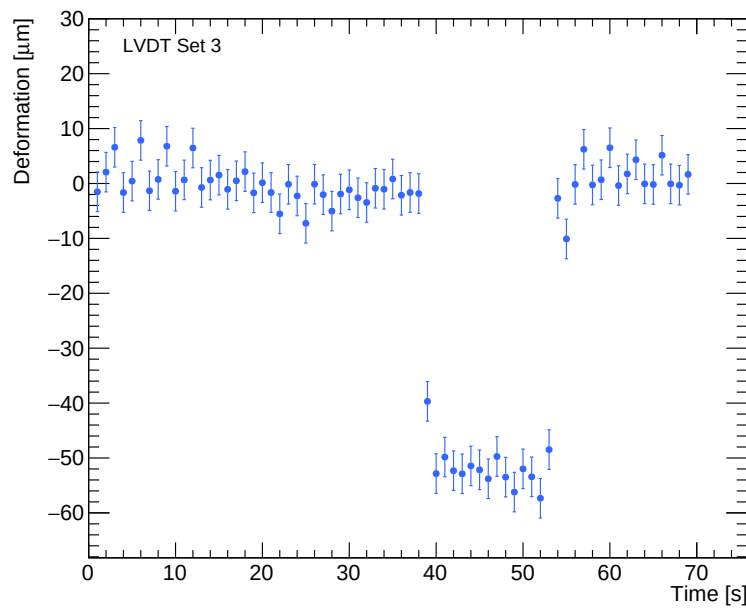


Figure 7.19: Absolute deformation recorded by the LVDT coils as a function of time. A statistical uncertainty on each point is assigned as per the results of section 7.3.2.

7.3.7 Thermal deformation measurement results

This section outlines the use of the LVDTs during a cooling test, whereby the thermal deformation of the global structure mock-up is measured.

To cool down the mock-up, dry-ice (solid CO_2 that sublimates) was placed around the mock-up in metal crates, and circulated with computer fans. The whole mock-up was enclosed with polyurethane insulating foam, and the edges were sealed with aluminium tape. Temperature sensors were placed in various positions around the mock-up, providing readings every second. The position of the rings as the temperature drops was monitored in real time by a set of LVDTs. Figure 7.20 shows various aspects of the cooling test. For this test, 25 kg of dry-ice was used.

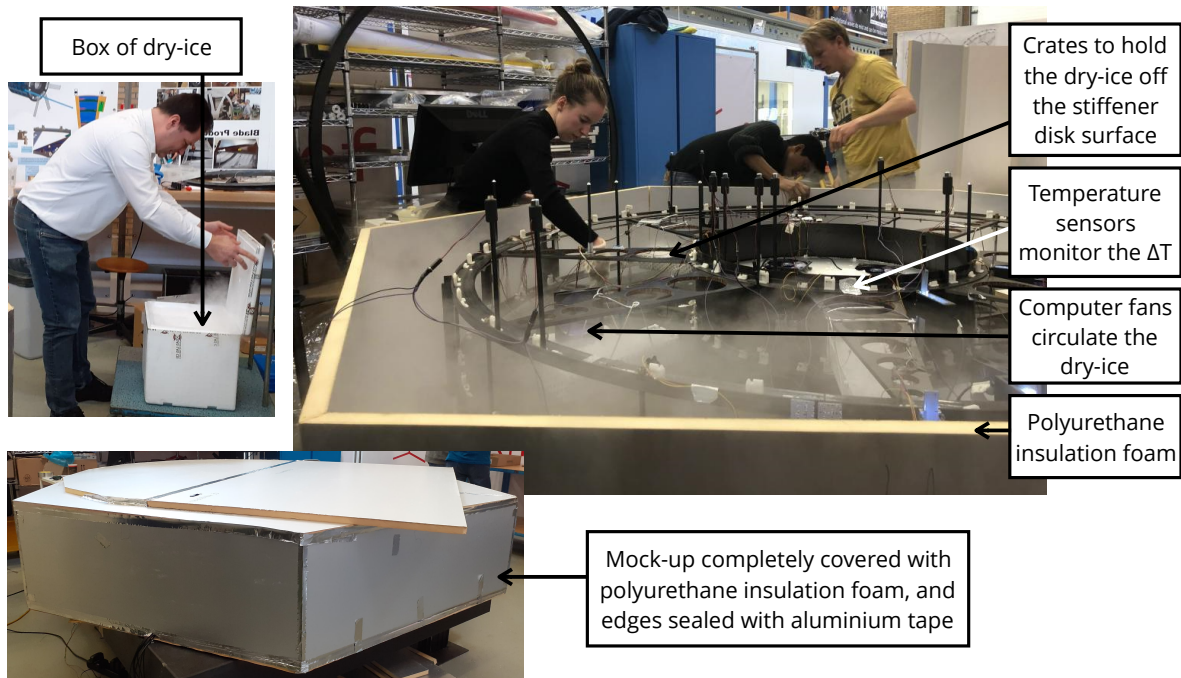


Figure 7.20: Images showing various aspects of the cooling test.

The specific placement of the LVDT set on the mock-up was decided by considering the mechanical structure of the end-cap, and what specific region was expected to deform more than others. As previously mentioned, due to nature of the carbon fibre winding, the rings are expected to be least stiff in the vertical direction between the upper and lower rings of the mock-up. Given this, the LVDT sets were placed between the upper and lower ring. Additionally, the LVDT set was placed half way between two spacer rods, which are carbon fibre rods especially stiff in the vertical

direction so to provide structural support to the rings. As such, the point between two spacer rods is expected to be where the largest deformation would occur. The location of the LVDT set mounted to the mock-up is shown in Figure 7.21.

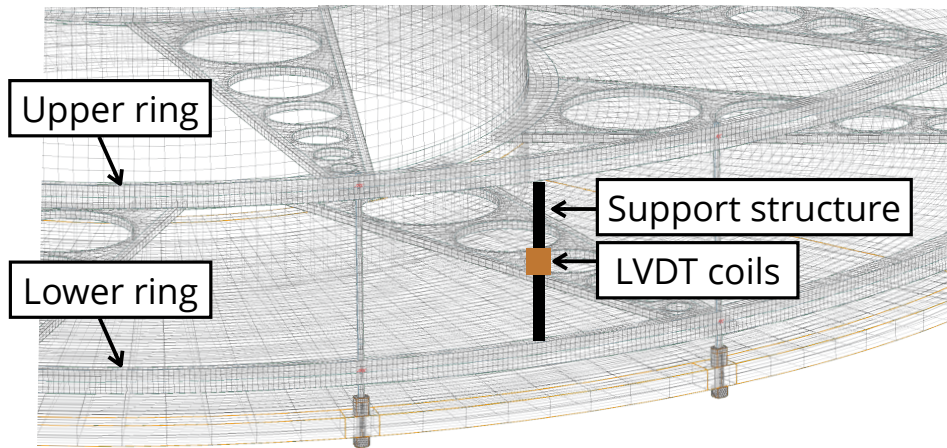


Figure 7.21: Technical drawing of a portion of the global structure mock-up, displaying the orientation of the LVDT coils which measure the relative displacement between the upper and lower rings. The LVDT coils are represented by the light brown coloured rectangle, while the black rectangles represent the support frames for the coils.

To provide an independent estimate of the thermal deformations, several other measurement devices were attached to the mock-up structure. Calipers were glued in various positions, along with cameras to take snapshots of the main scale over time, which would allow for an estimate of the relative ring deformation. The accuracy of this method is estimated to be $\sim 100 \mu\text{m}$. One caliper is positioned in such a way that a useful comparison of results between the caliper and the LVDT set could be made. Strain gauges provided an alternate approach to using LVDTs. These had to be glued onto the surface of the mock-up making them not ideal for measuring the final end-cap global structure components. Additionally, they only measured very local properties of the rings, meaning very close to the area surrounding the strain gauge itself.

The deformation results measured throughout the cooling test by the LVDT coils are shown in Figure 7.22 where the temperature effects on the mounts themselves, as calculated in section 7.3.5, have not yet been accounted for. Room temperature was recorded to be 21.25°C at the start of the cooling test. Once the dry-ice was been inserted around $t = 0.28$ hours, the insulation box was entirely sealed by $t = 0.43$ hours, and it took ~ 1 hour until the coldest temperature was reached. The temperature remained stable at -29.25°C , within a 5°C window, for roughly 40 minutes until the lid of the insulation box was removed. This occurred at $t = 2.2$ hours where the structure was allowed to naturally heat back up to room temperature. The small gap in measurement points between $2.47 - 2.50$ hours was due to a manual restart of the data recording device.

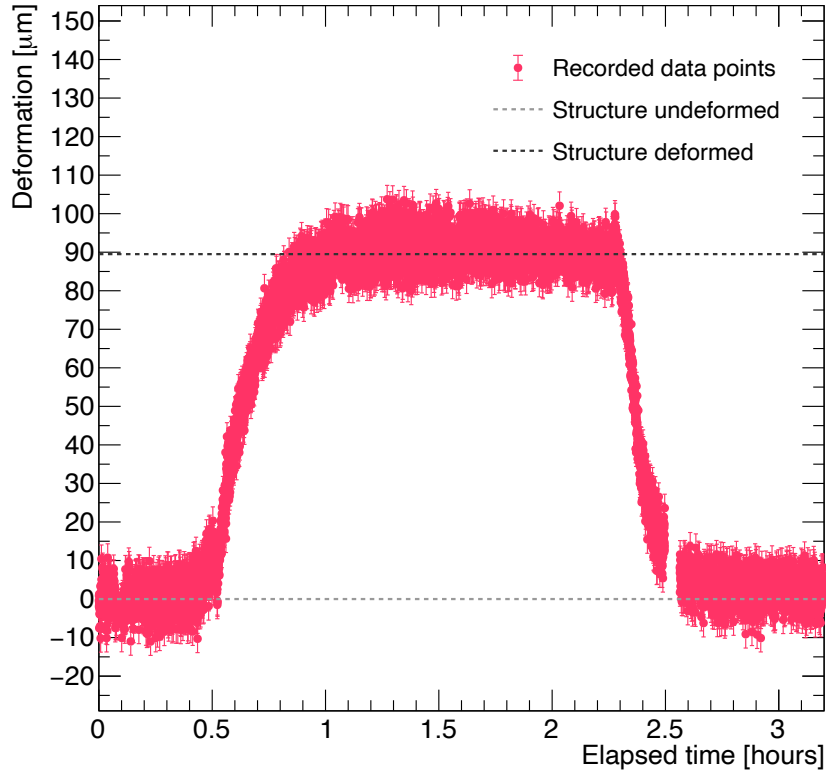


Figure 7.22: Deformation results obtained with the LVDT coils, during the dry-ice cooling test. Dry-ice was placed around the structure at $t = 0.28$ hours, and was removed at $t = 2.2$ hours. No temperature effects on the mounts themselves have been taken into account here. The uncertainty assigned to each voltage measurement is 6.6 mV: a combination of statistical and systematic uncertainties, as determined in sections 7.3.2 and 7.3.4.

The LVDT coils measure a relative deformation of $+89.1 \pm 5.5 \mu\text{m}$, where the positive sign indicates the upper and lower rings moved apart. This result is extracted from the plateau occurring between $t \sim 0.9 - 2.3$ hours in Figure 7.22. Taking into account the effects of temperature on the coil support frames, as per section 7.3.5, $-73.9 \pm 3.4 \mu\text{m}$ must be subtracted from the measured value to obtain the actual measured relative deformation between the two rings:

$$+15.3 \pm 6.4 \mu\text{m}. \quad (7.4)$$

The final result for the relative thermal deformation measured between the upper and lower rings is well within the specification required for the end-cap global structure, which was maximum $100 \mu\text{m}$.

At $t = 2.2$ hours the lid of the insulating box was removed, the remaining dry-ice taken out, and the mock-up naturally started returning to the ambient room temperature. The LVDT set continued recording voltage measurements to see if the rings returned to their original position

once the temperature reached $\sim +21.38^\circ\text{C}$. The final deformation value was $0 \pm 4.8 \mu\text{m}$, meaning no displacement from the initial position.

7.3.8 Discussion and interpretation

The relative thermal deformation between the upper and lower rings has been measured during the cooling test, and the results indicate movement well below the specification of $\lesssim 100 \mu\text{m}$. It would be ideal to obtain an independent measurement confirmation of the results obtained by the LVDT coils, although the motivation for this research was due to the lack of an existing real-time alignment monitoring system. The only comparison possible is between measurements recorded by a caliper located close to the LVDT system. This caliper measured a relative deformation between the upper and lower ring of $+100 \pm \sim 100 \mu\text{m}$ during the cooling test. The positive sign indicates the caliper measures deformation in the same direction as the LVDTs, indicating the results are generally compatible. Due to the large uncertainty however, a clear statement cannot be made about the agreement between the caliper and LVDT results. The strain gauge measurements were useful in determining the CTE of the various composite materials used in the mock-up structure, however weren't so easily converted to an equivalent deformation value.

The results obtained from the cooling test can also be compared to a somewhat equivalent finite element analysis (FEA). This analysis is a simulation of the mock-up structure which takes into account, in a fairly coarse way, the dimensions of the structure, the properties of the materials (namely the CTE values), and the change in temperature. It then calculates the expected deformation of the structure, according to the inputs. The main limitation of the FEA analysis is that it is, by construction, heavily dependant on the granularity with which you define the simulation as well as the uncertainty on input parameters. In this case the CTE values of the materials used to make the mock-up carry the largest uncertainty since the CTE values of the individual composite materials have not been precisely determined and are merely a rough estimate. The simulation does not replace or undermine the experimental measurements, but can be useful given the absence of other means for comparison. The result of the FEA analysis for the end-cap global structure mock-up with a $\Delta T = 50^\circ\text{C}$ is shown in Figure 7.23.

To compare the LVDT-measured deformation results with the FEA simulation the difference between the position of upper and lower rings in Figure 7.23 must be taken, since the displacement scale itself is arbitrary. The FEA analysis predicts the relative deformation to be $\sim -16 \mu\text{m}$, where the negative sign indicates the rings move closer together. The absolute size of the deformation is consistent between the FEA analysis and the measured LVDT deformation during the cooling test, but the direction of movement is not. This incompatibility does not undermine the validity of the LVDT obtained measurements given, as mentioned above, the FEA simulation carries a large degree of uncertainty.

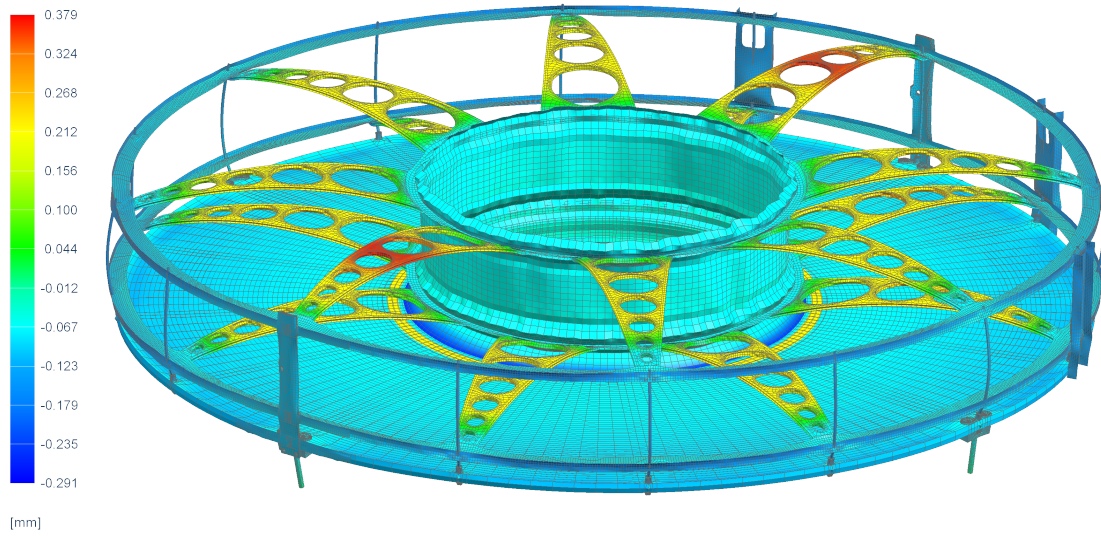


Figure 7.23: A finite element analysis (FEA) for the global structure mock-up, with $\Delta T = 50^\circ\text{C}$. The displacement scale shown is absolute so the difference between the upper and lower rings corresponds to the overall displacement.

7.3.9 Conclusion

The main goal of this research was to develop a real-time alignment system that could accurately measure the deformation of the ITk end-cap global structure when thermally cycled. This has been achieved with the LVDT system, which obtained a measurement accuracy of $5.5\ \mu\text{m}$ from equation 7.3. Two sets of LVDTs were attached to the end-cap mock-up, and used to take deformation measurements over a temperature range of $\Delta T \approx 50^\circ\text{C}$. The result obtained was that upper and lower rings moved apart by $+15.3 \pm 5.9\ \mu\text{m}$. This result is within the $100\ \mu\text{m}$ design specification.

The studies and results achieved, particularly in validating the LVDT system, mean an accurate system is available to take thermal deformation measurements when the final global structure components are ready. In particular, manufacturing of the stiffening disk (one that will ultimately be used in the ITk end-cap inserted into ATLAS for Phase II) was undertaken during 2021 - 2022, and 16 sets of LVDT coils were used to measure the thermal deformation of the stiffening disk, to ensure it adheres to the appropriate requirements. These results are presented in section 7.4.

7.4 Mechanical alignment of the ITk strip end-cap stiffening disks

The first component that was produced for the actual ITk end-cap global structure were the stiffening disks. These disks are made from carbon fibre sheets held together with a fire-retardant epoxy and filled with 12 kilograms of Ultem foam. They each measure two metres in diameter with a 74 cm diameter hole in the centre surrounding the beam pipe. The disks have a thickness

of roughly 3 cm at large radii, which increases to 8 cm towards the centre. In total three disks will be produced; two will be installed in ATLAS, and one remains a spare. This section details the thermal deformation measurements of the three fabricated stiffening disks, to confirm they satisfy the design specification. The results will dictate which two disks will be used for the end-caps, as well as confirm their structural behaviour is within the specifications.

As the LVDT alignment system was validated and used for the global structure mock-up, as per section 7.3, this measurement device will be also implemented to quantify the thermally induced deformations of the stiffening disks. For these measurements, industrially manufactured LVDT coils will be used instead of the in-house coils made at Nikhef. This primarily due to larger number of coils required for the whole global structure, given hand-making them is quite labour intensive, as well as minimising the inherent variations between handmade devices. The mechanism behind the coils is the same in both cases, the only difference being the coil components. A schematic diagram of the LVDTs that will be used to make the stiffening disk measurements is displayed in Figure 7.24.

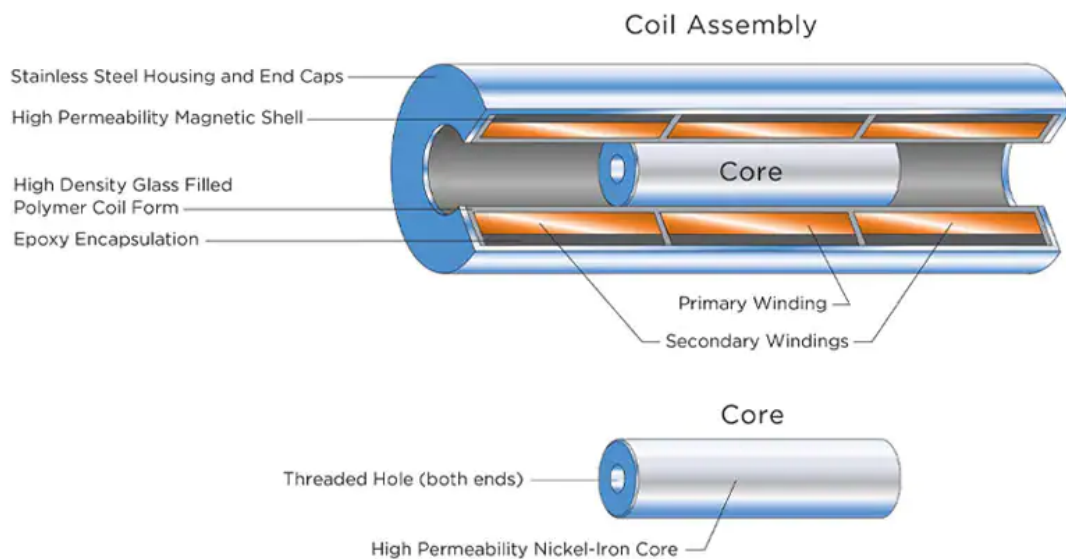


Figure 7.24: Schematic diagram of industry standard LVDT coils showing the location of the primary and secondary coil windings [134]. The central core is able to freely move horizontally within the coil assembly. The material used for each structural component is also labelled.

The specification for the stiffening disk, over a uniform temperature change of 45°C is a maximum deformation of 300 µm. Following the calibration of the LVDT coils, which is outlined in section 7.4.1, the coils were used to measure the stiffening disks structural response to a uniform change in temperature between $\sim -30^{\circ}\text{C}$ and 40°C . Two separate thermal tests will be conducted

to be sure no thermally-induced problematic structural effects are seen across and extended temperature range. A cooling test for the range $\sim +20^\circ\text{C} \rightarrow -30^\circ\text{C}$ will be performed, and a heating test for $\sim +20^\circ\text{C} \rightarrow +40^\circ\text{C}$. These tests are conducted separately given different methods are required in each case to alter the ambient temperature surrounding the stiffening disk. The experimental set-up used to conduct these tests is described in section 7.4.2. The results are presented and discussed in section 7.4.4.

7.4.1 Calibration studies

Eleven LVDT coils are used to measure the deformation of the stiffening disks. Each of these are individually calibrated to obtain the correct voltage to displacement conversion factor per set. Variation between the conversion factor obtained for the eleven LVDTs sets tested is expected to be minimal since these coils are manufactured according to specific industry standards to be within some pre-determined tolerance.

To calibrate the LVDTs, similarly to the procedure described in section 7.3.3, the core is placed near the very centre of the coils. A voltage reading was then taken for a series of known core positions, to obtain the correct voltage to displacement conversion factor. These measurements, taken for one LVDT set are display in Figure 7.25. Fitting the measurement points with a first order polynomial, $V(x) = \alpha \cdot x + \beta$, allows the conversion factor to be extracted, between the voltage reading and the corresponding displacement value. An example is seen in Figure 7.25 the results of LVDT coil set 5 calibration is shown, and the resulting conversion factor obtained is $5.2699 \pm 0.0017 \text{ mV } \mu\text{m}^{-1}$. The uncertainty on each voltage reading was 0.002 V, and 0.001 mm on the core position. The uncertainties for each data point are included in Figure 7.25 though not visible since they're smaller than the size of the markers used for the data.

The LVDT displacement measurement range is expected to be a few millimetres. As can be seen from the voltage residuals plot, shown in the bottom insert of Figure 7.25, no significant deviations are observed between the voltage readings and the fitted function obtained over a core position range of millimetres. This means the LVDTs, and the determined conversion factor, is suitable for measuring deformations of the global structure within this roughly 2.5 mm range.

The conversion factors obtained for each of the LVDT sets are displayed in Table 7.4.1. The average conversion factor is $5.293 \pm 0.007 \text{ mV } \mu\text{m}^{-1}$, corresponding to a conversion of roughly 200 μm per volt.

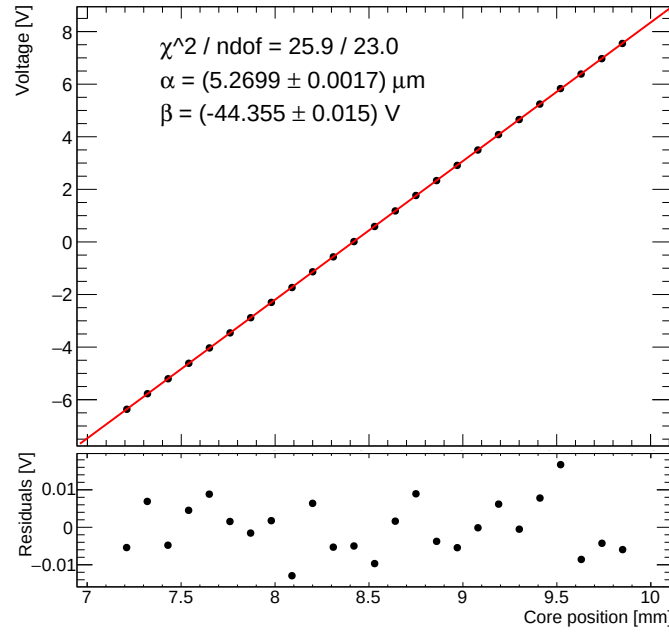


Figure 7.25: Voltage measurement points taken at various core positions for LVDT set 5. A first order polynomial function was fit to the data points, described by $V(x) = \alpha \cdot x + \beta$, where the fit value obtained for α corresponds to the required voltage to displacement conversion factor. The voltage and displacement uncertainties are displayed, although too small to be visible. The fit values obtained for α and β , and their associated uncertainty values are displayed.

LVDT set number	Conversion factor [$\text{mV } \mu\text{m}^{-1}$]	LVDT set number	Conversion factor [$\text{mV } \mu\text{m}^{-1}$]
1	5.319 ± 0.002	7	5.289 ± 0.002
2	5.250 ± 0.002	8	5.333 ± 0.002
3	5.325 ± 0.002	9	5.312 ± 0.002
4	5.221 ± 0.001	10	5.312 ± 0.002
5	5.270 ± 0.002	11	5.219 ± 0.002
6	5.319 ± 0.003		

Table 7.4: Voltage to displacement conversion factors obtained for all LVDT sets, by fitting the voltage measurements recorded at known core position points. For each set, a series of 10 calibration measurements were taken and the conversion factors obtained. The results presented in this Table represent the mean value obtained; the ascribed uncertainty is the standard deviation. Averaging these factors over all LVDT sets, the conversion factor obtained is $5.293 \pm 0.007 \text{ mV } \mu\text{m}^{-1}$.

7.4.2 Experimental set-up

An image of one of the three stiffening disks is shown in Figure 7.26a, with a close-up of how LVDT sets 1 and 2 are positioned with respect to the disk in Figure 7.26b. During the thermal deformation tests, the disk sits atop an aluminum support frame, and is housed inside an insulating

foam box (pictured with the lid removed) which is used to control the environmental temperature. Figure 7.27 indicates the location of all eleven LVDTs; sets 1, 3, 5, 7, 9, 10, 11 are all on one side of the disk, and sets 2, 4, 6, 8 are on the other. Various temperature sensors were also placed around the disk, and these are labelled TX, where X represents the sensor number.

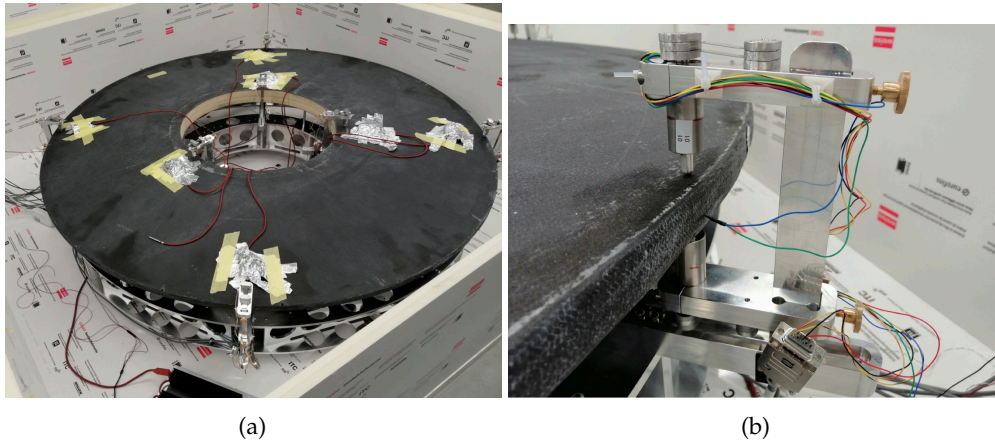


Figure 7.26: Mechanical alignment set-up for the ITk strip end-cap stiffening disk. Figure 7.26a shows one stiffening disk sitting on top of an aluminum support frame, inside an insulating foam box. The box allows for artificial temperature changes in the environment to occur, which is required to conduct thermal deformation tests. Figure 7.26b is a close-up of LVDT sets 1 and 2 as mounted either side of the stiffening disk to be able to measure the relative deformation due to temperature changes.

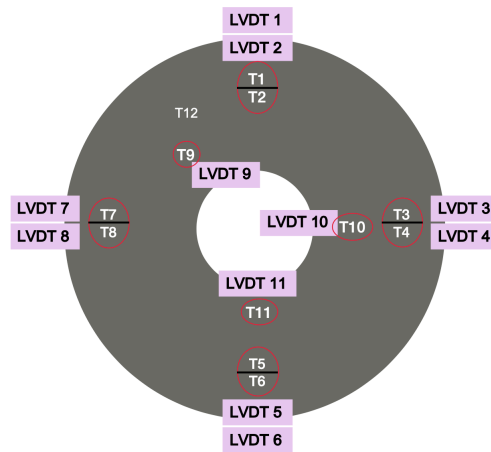


Figure 7.27: Location of LVDT displacement measuring sets and temperature sensors placed around the stiffening disk. Odd numbered LVDTs plus set 10 are placed on top of the disk, whilst the remaining even numbered sets are placed on the reverse side.

The goal is to determine the thermally induced deformation of the stiffening disk, noting that temperature changes will also induce deformations of the aluminum support structure on which the stiffening disk is placed. In addition to this, the aluminum support frames which hold the LVDT sets will also undergo structural deformations. To take these into account, the disk deformation

is calculated in two different orientations of the disk, such that the difference can be taken which will remove the deformation due to these external global effects. Deformation measurements are taken when the disk is placed with the flat side *down* and then *up*. These orientations are defined in Figure 7.28. While the disk is facing down, the displacement due to the disk and the set-up contribute in the same direction. When the disk is flipped, the sign of the stiffening disk displacement changes, which that of the set-up remains the same. In this way, the deformation due to the disk alone can be extracted. A sagitta parameter (will be defined in section 7.4.3), defines the calculated deformation across the stiffening disk plane.

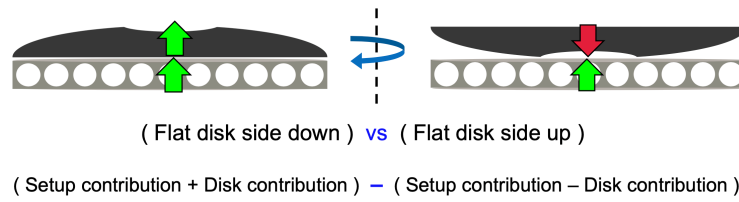


Figure 7.28: The two measurement orientations of the stiffening disk, *down* and *up* according to the orientation of the flat side of the disk. To remove the contribution from the set-up support structures, measurements in both orientations are taken and then subtracted from one another, thus leaving only the deformation due to the stiffening disk.

7.4.3 Calculation of the sagitta parameter

The *sagitta* parameter is defined by considering two planes across the surface of the stiffening disk: one axis runs from LVDT set 1, through the centre of the disk, to LVDT set 5 (denoted 1-C-5), whilst the second axis is perpendicular to this running from LVDT set 3 through the centre again, to LVDT set 7 (denoted 3-C-7), as shown in Figure 7.29. To determine the centre point, the measured values obtained from LVDT set numbers 9, 10 and 11 are taken and averaged to give roughly the deformation in the central disk-less region of the structure. In this way, the sagitta value quantifies the relative out-of-plane deformation of the stiffening disk centre with respect to the edges, and thus captures the overall deformation of the stiffening disk. For each thermal test, once the individual LVDT measurements have been made, the two sagitta quantities can be calculated to extract the deformation due to the stiffening disk alone.

7.4.4 Results

To assess the response of the stiffening disks to temperature changes, four separate thermal tests are conducted, which proceed as follows. The three disks are heated from room temperature to $\sim +40^\circ\text{C}$ using two heaters. Then the disks are cooled down from room temperature to $\sim -30^\circ\text{C}$ by placing dry ice inside the foam box, and using fans to circulate the air. Although the specification was for a temperature change of $\Delta T = 45^\circ\text{C}$, the heating test provided a slightly extended

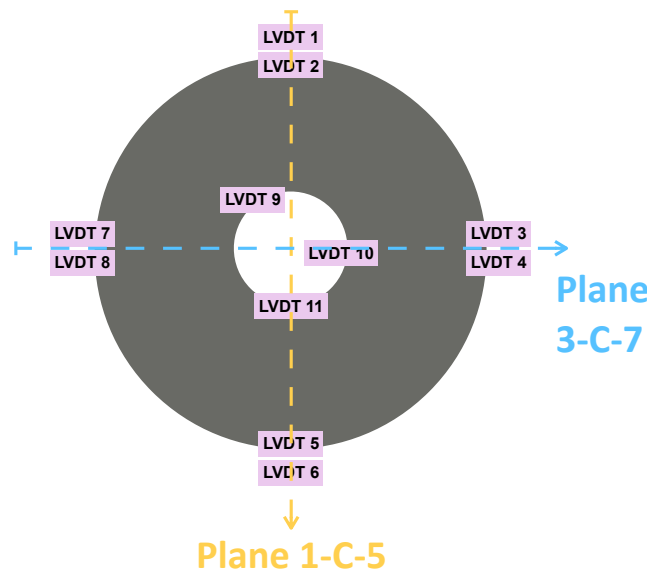


Figure 7.29: Diagram illustrating the definition of the two planes used to define the sagitta parameter. The 1-C-5 axis is defined by combining the measurements taken by LVDT set 1, the centre, and LVDT set 5. Similarly the 3-C-7 axis uses LVDT sets 3 and 7. The centre point is calculated by averaging the measurements taken by LVDT sets 9, 10 and 11. The position of each of the LVDT sets is indicated.

temperature range to more broadly understand the thermal effects of the structure that strictly required by the specification. The deformation of the support structure alone is removed from the total measured deformation, as discussed in section 7.4.2. The sagitta can subsequently be calculated as described in section 7.4.3; the resulting deformation of the disk in each of the two planes during the thermal tests are presented in Table 7.5. The measured deformations of stiffening disk number one is the largest, and does not satisfy the required specification. On the contrary, disk numbers two and three both deform less than the required upper limit. For the construction of the final ITk strip endcaps, disk one will be kept as the spare and disks two and three will be used.

Stiffening disk	Deformation 1-C-5 [μm]	Deformation 3-C-7 [μm]
1	524	101
2	128	32
3	99	285

Table 7.5: Deformation results of the defined planes 1-C-5 and 3-C-7 obtained during thermal tests of the stiffening disks. All presented values have an uncertainty of $50\mu\text{m}$ due to the systematic uncertainties associated with the experimental set-up used. Disk 1 will be kept as the spare, since it has produced the largest deformations. Disk 2 and 3 behave within the design specifications.

7.4.5 Conclusion

This section presents the results of thermal deformations tests conducted on the three stiffening disks manufactured at Nikhef, in order to ascertain if their mechanical behaviour satisfies the design specification. Specifically, a deformation smaller than $300\text{ }\mu\text{m}$ is required across a temperature change of 45°C . Thermally induced deformations of the structure have been measured by calculating the global deformation across two measurement planes of the disks, where the global movement due to the support structures was accounted for. The measurement results obtained indicate that the stiffening disk labelled as number one deforms larger than desired, so it will be kept as the spare. Disk numbers two and three will be installed in the two ITk strip end-cap global structures.

7.5 Conclusion

The HL-LHC physics programme provides a new landscape of exploration for Higgs boson precision measurements, as well as probing unexplored regions of phasespace to continue the search for physics beyond the SM. This chapter has outlined the planned ATLAS detector upgrades required to keep up with the challenging conditions expected during the HL-LHC data-taking period. A specific focus has been placed on describing the strip component of the ITk upgrade, given Nikhef's involvement in fabricating the two end-cap global structures as was the focus of this chapter.

To measure the mechanical properties of the global structure, an accurate alignment measuring system has been validated and proposed for use to conduct these measurements. The LVDTs proved to be both precise and robust, despite the numerous challenges associated with taking thermal deformation measurements of a structure of this size. LVDTs were used initially to confirm the mock-up of the end-cap rings satisfied the requirement to deform less than $100\text{ }\mu\text{m}$ across a temperature change of $\sim 50^\circ\text{C}$, to ensure structural integrity is maintained during the detector operating conditions. Once the stiffening disks were produced (two to be used, and one as a spare), LVDTs were again used to check the overall deformation of the structure. These tests were used to select the two stiffening disks to be integrated into the ITk.

Throughout 2022 and 2023, the remaining structural components of the ITk were fabricated and assembled in a dedicated clean-room area in the mechanical engineering workshop at Nikhef. An example of one of the fully assembled ITk end-cap global structures is shown in Figure 7.30. One of the two completed end-caps will be sent to DESY in Hamburg, and the other will remain at Nikhef. The petal installation and testing phase will be undertaken for each end-cap, at the respective institutes.

The HL-LHC is anticipated to commence collisions in 2029.

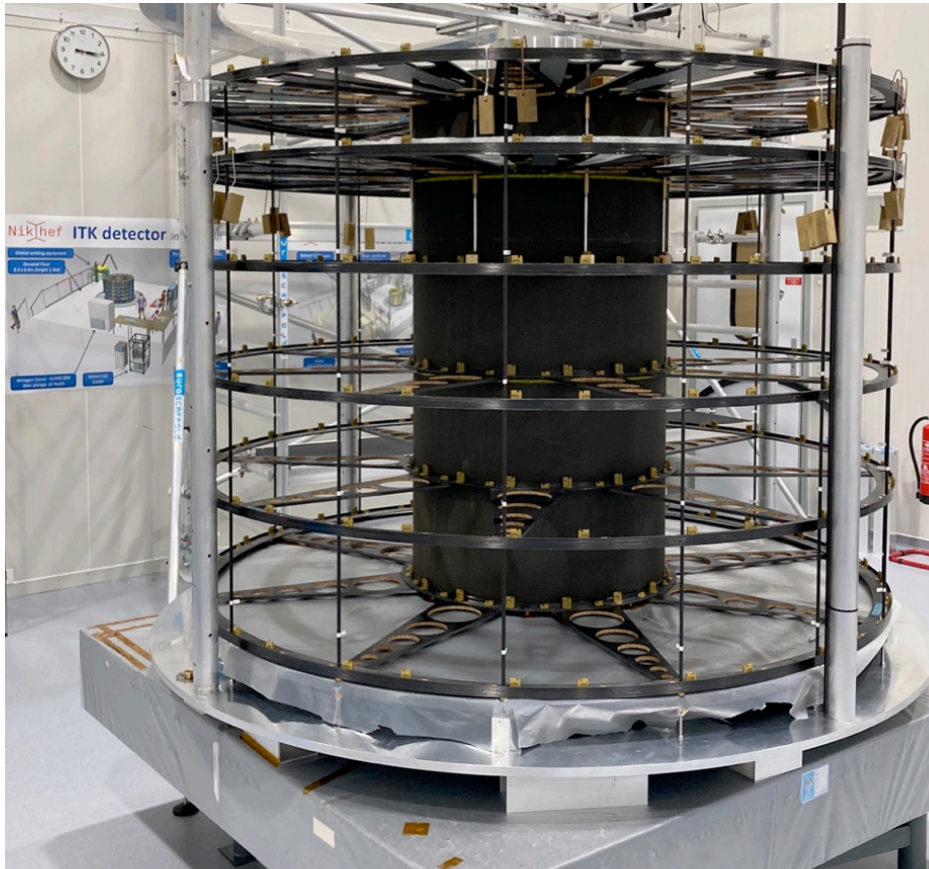


Figure 7.30: Image of one fully assembled ITk strip end-cap global structure.

8 | Conclusion

The Run 2 ATLAS physics programme has provided an abundance of new and interesting Higgs boson property measurements, one of which has been presented in this dissertation. The determination of the Higgs boson width has been presented, where the constraining power in the discussed analysis comes from the effects caused by the interference between signal and background events in the diphoton decay channel. In particular, the gg and qg initiated interference effects have been included, which are the dominant contributions. In the $\gamma\gamma$ decay channel specifically, the presence of interference causes a shift in the position of the resonance peak as well as an effect on the total yield, which we exploit by defining a simultaneous shape fit over the $m_{\gamma\gamma}$ distribution between 105 and 160 GeV (split into 550 bins). To enhance the experimental sensitivity, two event categories have been defined by making a selection on the transverse momentum of the diphoton system.

The observed (expected) upper limit on the Higgs boson width has been determined to be $\Gamma_H < 54.1 \cdot \Gamma_H^{\text{SM}}$ ($59.2 \cdot \Gamma_H^{\text{SM}}$) at the 95% C.L., when fixing $\mu = 1$ and $m_H = 125$ GeV. The theoretical prediction for the Higgs boson width in the SM is $\Gamma_H^{\text{SM}} = 4.09$ MeV. The difficulty in this analysis arises from the fact that the induced interference effects on $m_{\gamma\gamma}$ are small, whilst there are several systematic uncertainty components which would need to be significantly reduced to be able to provide a measurement of the Higgs boson width. In particular, uncertainties on the gg -interference cross-section, as well as uncertainties related to the MC generation procedure stand to make significant improvements to the experimental sensitivity. The sensitivity is expected to improve by roughly a factor six following the analysis of 3000 fb^{-1} of data scheduled to be collected by ATLAS during the HL-LHC data-taking period, which will drastically reduce the statistical uncertainty. Extrapolating the Run 2 analysis result indicates an upper limit of the Higgs boson width of $\Gamma_H < 13.9 \cdot \Gamma_H^{\text{SM}}$ can be expected. Construction of the ATLAS detector in anticipation for the HL-LHC phase is progressing; no doubt there is an abundance of new physics waiting to be uncovered.

Summary

If you gaze up at the sky on a clear night in Melbourne, you'll see the stars of the Southern Cross glistening between Alpha Centauri and the Southern Pleiades. These stars, along with all other visible matter in the universe, are comprised of only three elementary particles: the so-called *up*-type quark, *down*-type quark, and the electron, which are the basic building blocks of an atom. Many more than these three fundamental particles exist in nature, and form what is known as the Standard Model of particle physics. This model describes all of the known elementary particles, including their properties and how they interact. We know today there are three generations of particles, where those making up the atom correspond to the first generation, as well as four types of force carrying particles which mediate the particle interactions. The Higgs boson was the final predicted particle in the Standard Model to be discovered; this was achieved in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider at CERN, where the combined measured mass of the Higgs boson was observed to be $m_H = 125.09 \pm 0.24$ GeV [115].

The Higgs boson observation was a major step in furthering our understanding of the universe, given its imperative role as the mechanism behind mass generation in the Standard Model. The Run 1 data-taking period which spanned 2010 to 2012 allowed for fundamental properties of this new particle to be measured for the first time, in order to gain a preliminary understanding of whether this particle in fact corresponds to that predicted to exist by the Standard Model. Such properties included the first measurement of the Higgs boson's mass, spin, parity, and couplings (primarily to the gauge bosons). The measurements are so far consistent with the Standard Model expectations, however we know that the Standard Model fails to account for numerous experimental observations, therefore motivating the need for further investigation and higher precision measurements.

The significant increase in data collected during the 2015 to 2018 Run 2 data-taking period opened the doors to a precision era of Higgs boson physics where an abundance of previously statistically-limited measurements could be made, as well as improving on the accuracy of property measurements like the mass and couplings. The total decay width, which is related to the decay lifetime of the Higgs boson, is one property beyond the experimental reach attainable with the Run 1 dataset. The Run 2 dataset instead allowed for the possibility of determining this property via numerous experimental techniques, one of which is through the measurement of quantum interference effects in the $H \rightarrow \gamma\gamma$ decay channel, which will be outlined below.

The Higgs boson decay lifetime

Few particles in nature are truly stable, the electron and photon are two examples, the rest are unstable and decay via specific decay channels, or *modes*, to other particles. The decay lifetime, τ of an unstable particle is inversely proportional to the total decay width, Γ , which is defined as the sum of all allowed partial decay modes, i as:

$$\tau = \frac{\hbar}{\Gamma}, \quad \text{where } \Gamma = \sum_{i=0}^n \Gamma_i. \quad (8.1)$$

For a fundamental particle, the total decay width corresponds to the width of its invariant mass distribution. For a Higgs boson with mass around 125 GeV, the theoretical prediction for the total decay width [3] is:

$$\Gamma_H^{\text{SM}} = 4.09 \pm 0.16 \text{ MeV}. \quad (8.2)$$

Since the total decay width is defined by directly summing all the partial decay modes, should a new unpredicted Higgs boson decay channel exist, this would alter the value of Γ_H . For example if a dark matter particle coupled to the Higgs boson, this would increase the number of allowed decay channels which result in a larger than expected total decay width. For this reason, the Higgs boson width is an ideal probe of new physics, and measuring its value precisely is of paramount importance given it may hint at the existence of physics beyond the Standard Model.

The Higgs boson at the LHC

The Large Hadron Collider (LHC) is located at the *Conseil Européen pour la Recherche Nucléaire* (CERN) in Geneva, Switzerland. The ATLAS detector sits at one of the four interaction points around the 27 kilometre LHC ring; the CMS, LHCb, and ALICE detectors are located at the other three, each with their own physics goals and hence unique detector designs. The ATLAS detector can be thought of as a huge camera which takes *pictures* of the spray of particles produced in the collisions. These collisions occur between two beams of protons, where the colliding groups are known as *bunches*; one bunch contains 10^{11} protons which travel at up to 99.9999990% of the speed of light, and collide at energies between 7 TeV in 2010 and up to 13.6 TeV in 2024. Since the proton is not a fundamental particle, collisions actually occur between the proton constituents; either the quarks or gluons that make up the proton. The diagram shown in Figure 8.1 depicts this nature of proton-proton (pp) collisions at the LHC.

The Run 2 data-taking period occurred at a collision energy of $\sqrt{s} = 13 \text{ TeV}$. At this energy, the dominant Higgs boson production mode, for a Higgs boson with mass $m_H = 125 \text{ GeV}$, occurs when two gluons collide and annihilate to produce a Higgs boson, known as gluon-gluon fusion (ggF). Once a Higgs boson is produced it decays, as mentioned above after only $1.6 \times 10^{-22} \text{ s}$ on

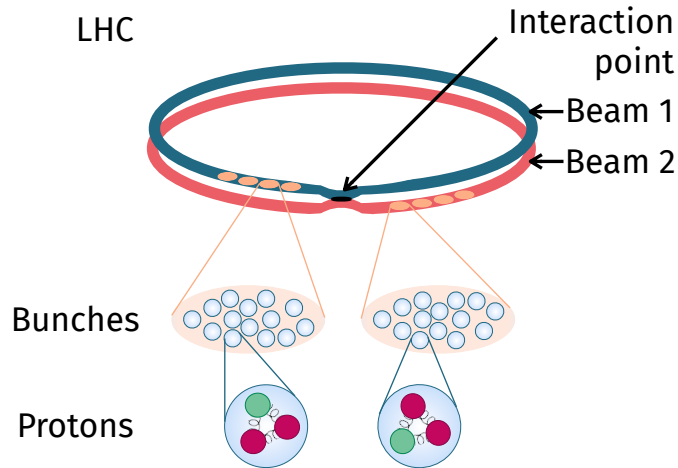


Figure 8.1: Overview of proton-proton collisions at the LHC. Protons are accelerated around the LHC ring in bunches which each contain 10^{11} protons, and are made to collide at designated interaction points. Collisions occur between quarks and gluons that make up the individual protons.

average, via one of many possible decay channels. The dominant decay channel for a Higgs boson with mass around 125 GeV is $H \rightarrow b\bar{b}$ which occurs roughly 58% of the time. Since the Higgs boson couples to mass, there is no direct interaction in the Standard Model theory between the Higgs boson and a massless particle, like for example the photon. The $H \rightarrow \gamma\gamma$ decay channel therefore proceeds via a virtual loop containing massive particles and consequently is suppressed, occurring only 0.2% of the time [3].

The ATLAS detector is used to perform Higgs boson property measurements by measuring particles produced in pp collisions, which traverse the detector layers and leave *hits* in the form of energy deposits. The innermost ATLAS sub-component is the inner detector, which is a silicon plus gaseous tracking system used to measure charged particle trajectories (tracks) and decay locations (vertices). A 2 T magnetic field surrounds the inner tracker such that the measured charged particles tracks are curved, and the radius of this bending allows for the momentum of the particle to be determined. Moving outwards, the next sub-detector is the electromagnetic calorimeter which is responsible for measuring energy deposited by electromagnetic showers of electrons and photons, followed by showers induced by hadrons such as protons and neutrons, which are measured by the hadronic calorimeters. The final sub-detector system is the muon spectrometer which, along with the inner detector, measures the tracks left by muons as they traverse the entire detector. The muon spectrometer is immersed in a toroidal 4 T magnetic field which causes the muon trajectories to be bent as they pass through. Since proton bunches are collided every 25 ns, this corresponds to a collision frequency of 40 MHz, and thus a total data rate of around 40 TB per second. A series of trigger systems, both online and offline, are required to substantially reduce this data rate to a more manageable size. In the end, about 1.5 GB of data per second is permanently saved and used for physics analysis.

The ATLAS detector has been used to study properties of the Higgs boson in the $H \rightarrow \gamma\gamma$ decay channel since 2011; it was one of the two channels used for the discovery, the other being $H \rightarrow ZZ^* \rightarrow \ell^-\ell^+\ell^-\ell^+$, where $\ell = e, \mu$. Despite the relatively low decay probability, the $H \rightarrow \gamma\gamma$ channel has a unique experimental signature in that it leaves two collimated electromagnetic showers, corresponding to the two photons, in the electromagnetic calorimeter. This is despite the fact that the cross-section for this process is several orders of magnitude lower than the dominant background processes which don't involve the Higgs boson, as illustrated in Figure 8.2. Specific selection criteria are required to be applied to data to maximise the number of signal events while removing the background contributions as much as possible, to enhance the experimental sensitivity.

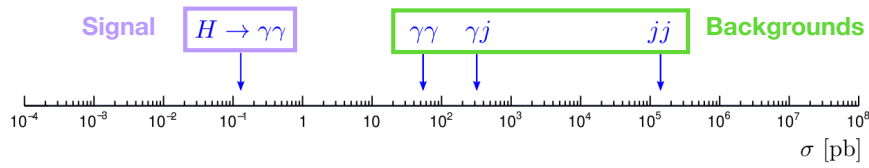


Figure 8.2: Cross-section value for the signal $H \rightarrow \gamma\gamma$ decay channel, compared to the cross-section for the three dominant sources of background events coming from Standard Model $\gamma\gamma$, γ +jet, and jet-jet production.

Interferometry in $H \rightarrow \gamma\gamma$ decays

This thesis presents the determination of the Higgs boson width using the $H \rightarrow \gamma\gamma$ decay channel. The most intuitive way to measure the Higgs boson width would be to directly measure the width of the Higgs boson invariant mass distribution, which in this particular channel corresponds to the diphoton invariant mass distribution, $m_{\gamma\gamma}$. This observable is defined in terms of the energies and the angle, θ , between the two photons as:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}, \quad (8.3)$$

where E_1 and E_2 is the energy of the most energetic, and second most energetic photons present in final state. The precision of this direct method is heavily restricted by the ATLAS detector resolution, which is on the order of 1 GeV [51] (orders of magnitude above the expected intrinsic width of the distribution, as stated in equation 8.2). As such, indirect techniques must be used instead; this thesis focusses on exploiting such method which exploits effects in $m_{\gamma\gamma}$ invariant mass distribution which are caused by the presence of interference in the $\gamma\gamma$ decay channel.

Quantum interference occurs between any processes with the same initial state particles and final state particles. In this case, the dominant Higgs boson resonant signal is $gg \rightarrow H \rightarrow \gamma\gamma$, which

interferes with the background contribution which proceeds without the Higgs boson as $gg \rightarrow \gamma\gamma$. The Feynman diagrams corresponding to these two processes are shown in Figure 8.3. The

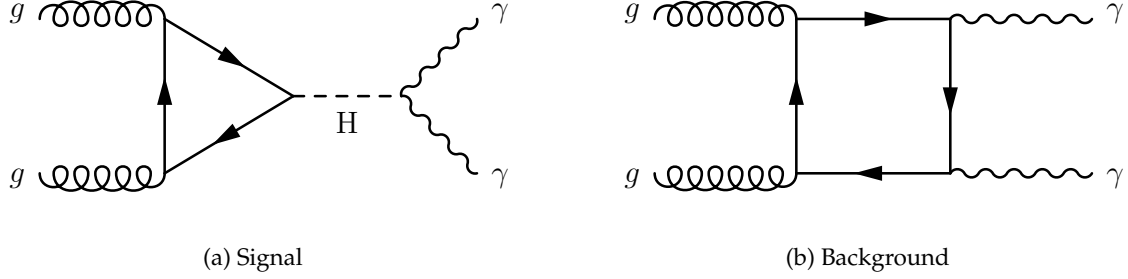


Figure 8.3: Feynman diagrams corresponding to the dominant production mode of the Higgs boson in the diphoton decay channel (signal process), $gg \rightarrow H \rightarrow \gamma\gamma$ (8.3a), as well as the background process, $gg \rightarrow \gamma\gamma$ (8.3b)

presence of this gg -induced interference on the resonant signal invariant mass distribution is firstly to cause a distortion in the peak itself. This is due to the shape of the interference itself which, when combined with the signal, causes a sizeable *mass shift* in the peak of the distribution towards lower values of $m_{\gamma\gamma}$. The predicted size of this mass shift in the SM is around 100 MeV at leading order precision [40], which reduces to around 70 MeV at next-to-leading order accuracy [4]. This mass shift is related to the Higgs boson width, and as such a measurement of the mass shift allows for an indirect determination of the width, Γ_H . This relationship is shown in Figure 8.4, where the theoretical dependence has been calculated at both next-to-leading order and next-to-next-to-leading order under a specific approximation.

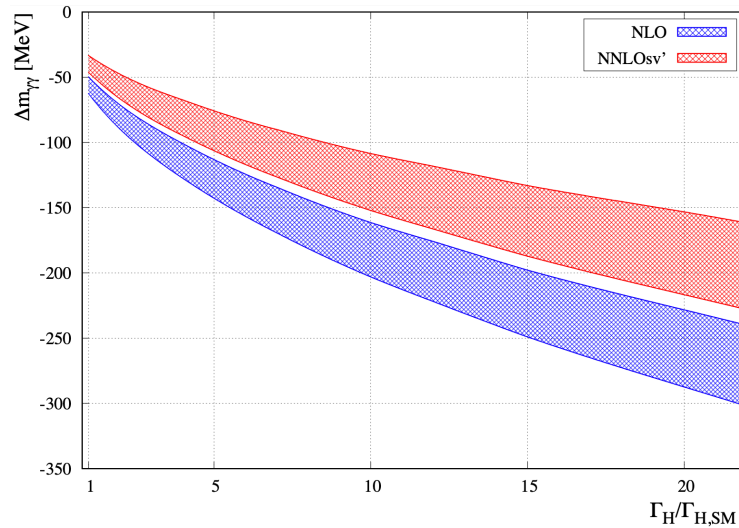


Figure 8.4: Mass shift, $\Delta m_{\gamma\gamma}$, as a function of the SM-normalised Higgs boson width [41], which has been computed at next-to-leading order (NLO), and next-to-next-to-leading order accuracy (NNLOsv'). The band quantifies the size of the theoretical uncertainty.

The interference contribution also causes a reduction in the overall cross-section, when compared to the expected signal-only yield. This reduction is predicted to be on the order of 1-2% at next-to-leading order [43, 44]. In addition to the dominant gg -interference, there are also sub-dominant effects due to qg -induced interference which also impacts the measured $m_{\gamma\gamma}$ distribution. This has a similar shape to the gg -interference, with the exception that the observed peak and dip structure is flipped with respect to the qg -interference, and so causes a shift towards high values of $m_{\gamma\gamma}$ on the order of 30 MeV [45]. As such the total mass shift expected when taking into account both the gg - and qg -interference is around 30% less than when including the gg -interference alone.

To enhance the experimental sensitivity, events are split into two *categories*, by defining a selection on the transverse momentum of the diphoton system, $p_T^{\gamma\gamma}$. Category 1 is defined by the selection $p_T^{\gamma\gamma} < 30$ GeV, while category 2 contains events in the $p_T^{\gamma\gamma} \geq 30$ GeV region. This strategy derives from the fact that the interference cross-section is proportional to the squared sum of the signal and background amplitudes, and the signal $p_T^{\gamma\gamma}$ distribution peaks at lower values, hence the effects due to interference are expected to be dominant in this region. This choice has been made since it allows for the measurement to be performed entirely in the $H \rightarrow \gamma\gamma$ decay channel, which can lead to a partial cancellation in the experimental systematic uncertainties since no ‘reference mass’ (meaning the Higgs boson mass as measured with little to no interference effects present) from another decay channel needs to be used.

Figure 8.5a shows the $m_{\gamma\gamma}$ distribution for the individual resonant signal, gg -interference and qg -interference contributions, where the interference has been scaled by a factor 10 for visualisation purposes. Figure 8.5b displays the resulting effect on the $m_{\gamma\gamma}$ distribution using simulated events; the resonant signal only distribution is shown in red, while the combined signal and interference distribution is shown in blue. The relative difference in the peak positions between these two distributions is 69.3 MeV.

Measuring the $m_{\gamma\gamma}$ distribution across the entire peak region, $120 < m_{\gamma\gamma} < 130$ GeV, allows for both the shape and yield affects to be accounted for such that the Higgs boson width can be determined; this is the procedure presented in this thesis. Analytical functions are used to model each of the signal, interference and background contributions separately, which define the combined model used to simultaneously fit the data $m_{\gamma\gamma}$ distribution. The total model fitted to the observed data is shown in Figure 8.6 for the two event categories used in the analysis. This dataset corresponds to 140.1 fb^{-1} of data collected by ATLAS during the Run 2 data-taking period. Performing a likelihood fit of the defined model to this data, including both statistical and systematic uncertainties, allows for a constraint to be placed on the Higgs boson total decay width, where the observed (expected) upper limit on the Higgs boson width is $\Gamma_H < 221.3$ MeV (242.0 MeV) at a 95% confidence level.

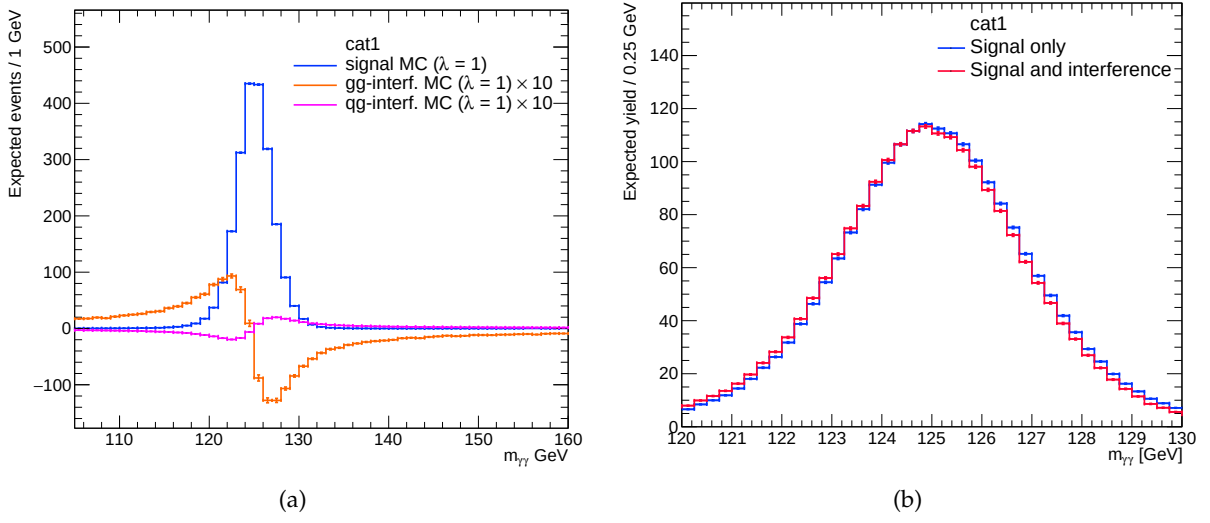


Figure 8.5: Invariant mass distributions in the diphoton decay channel in the analysis category defined by $p_T^{\gamma\gamma} < 30$ GeV. Simulated events have been used to produce these distributions. Figure 8.5a displays the individual distributions for the resonant signal, gg -interference, and qg -interference processes, where the interference has been scaled by a factor 10. Figure 8.5b shows the expected $m_{\gamma\gamma}$ distribution for the resonant signal process only (red), as well as the resulting distribution when both the signal and interference processes are included (blue).

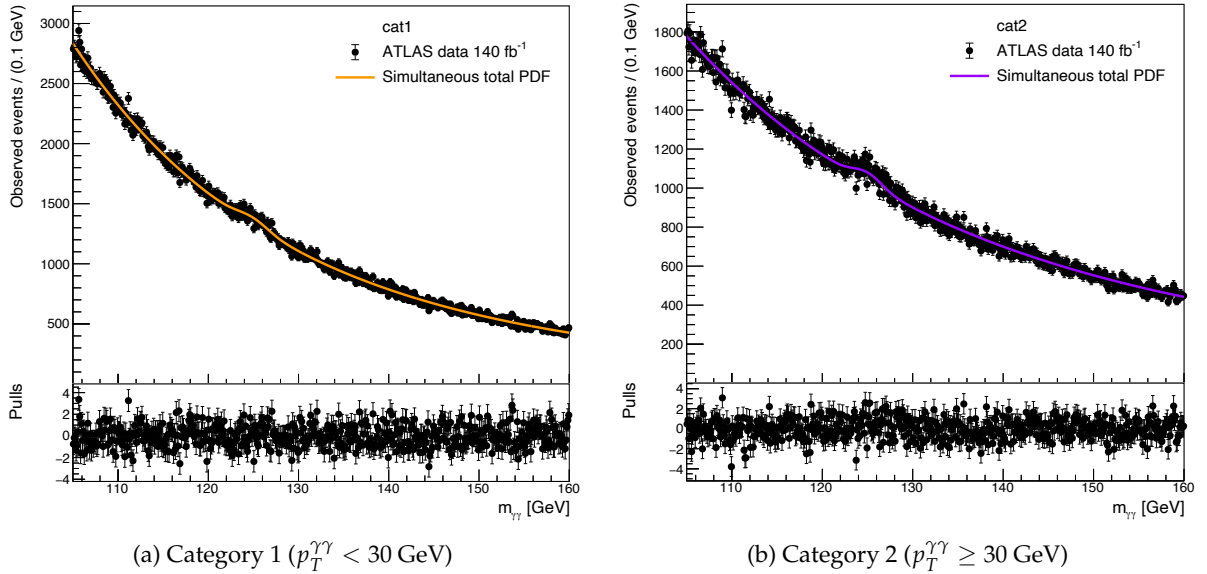


Figure 8.6: Invariant diphoton mass distributions using the ATLAS Run 2 dataset, where the data is shown in black and the total signal, interference and background model is shown overlaid by the coloured line. Figure 8.6a displays the distribution in category 1 used in the analysis ($p_T^{\gamma\gamma} < 30$ GeV), while Figure 8.6b corresponds to category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

Future prospects

The experimental sensitivity to the Higgs boson total decay width, Γ_H , achievable by exploiting interference effects is significantly limited primarily by the statistical uncertainty. A measurement

on a larger dataset would allow for a more precise determination of Γ_H . The High-Luminosity Large Hadron Collider (HL-LHC) is the scheduled upgrade of the existing LHC to a higher luminosity collider, and is expected to commence collisions in 2029. The HL-LHC data-taking period is expected to run for at least the subsequent decade, at which time the ATLAS detector is anticipated to record 3000 fb^{-1} of data. A projection study has been undertaken as part of this thesis which estimates the upper limit on the Higgs boson width achievable by the end of the HL-LHC is $\Gamma_H < 59.9 \text{ MeV}$ at a 95% confidence level. This result was extrapolated from the Run 2 analysis result accounting for the reduced statistical uncertainty, but did not include potential improvements in the analysis strategy or expected reductions in the systematic uncertainties. It is therefore not unrealistic to expect that following the analysis of the dataset collected by ATLAS during the HL-LHC period, a measurement of the Higgs boson width using interferometry may be within reach.

This thesis presents the analysis of $H \rightarrow \gamma\gamma$ decays used to determine the Higgs boson decay width, through the exploitation of interference effects. This result allowed for the Higgs boson width to be probed in a way that is complementary to other existing experimental methods. Given the relationship between the Higgs boson width and the possible decay channels of the Higgs boson, it is of vital importance to continue measuring this property, such that new physics, wherever it may be hiding, can be uncovered.

Samenvatting

Als je op een heldere nacht in Melbourne naar de hemel kijkt, zie je de sterren van het Zuiderkruis glinsteren tussen Alpha Centauri en de Zuidelijke Pleiaden. Deze sterren, samen met alle andere zichtbare materie in het universum, zijn opgebouwd uit slechts drie elementaire deeltjes: de zogenaamde *up*-quark en *down*-quarks en het elektron, die samen de basisbouwstenen van een atoom vormen. In de natuur bestaan veel meer dan alleen deze drie fundamentele deeltjes en al deze deeltjes samen vormen wat bekend staat als het Standaardmodel van de deeltjesfysica. Dit model beschrijft alle bekende elementaire deeltjes, inclusief hun eigenschappen en hoe ze met elkaar wisselwerken. We weten tegenwoordig dat er drie generaties van deeltjes zijn, waarbij de deeltjes die het atoom vormen de eerste generatie zijn, en vier soorten krachtoverdragende deeltjes die zorgen voor de interacties tussen de deeltjes. Het Higgs-boson was het laatst voorspelde deeltje in het Standaardmodel dat ontdekt moest worden; dit werd werkelijkheid in 2012 toen door de ATLAS- en CMS-experimenten bij de Large Hadron Collider bij CERN de gecombineerde massa van het Higgs-boson werd gemeten als $m_H = 125.09 \pm 0.24$ GeV [115].

De waarneming van het Higgs-boson was een belangrijke stap in het verdiepen van ons begrip van het universum, gezien de cruciale rol van het Higgs mechanisme bij het genereren van massa in het Standaardmodel. De gegevensverzamelingsperiode van Run 1, van 2010 tot 2012, maakte het mogelijk om de fundamentele eigenschappen van dit nieuwe deeltje voor het eerst vast te stellen, om zo een eerste idee te krijgen of dit nieuwe deeltje inderdaad overeenkomt met het deeltje dat volgens het Standaardmodel zou moeten bestaan. Dergelijke eigenschappen omvatten de eerste meting van de massa, spin, pariteit en koppelingen van het Higgs-boson (voornamelijk met de ijkbosonen). De metingen zijn tot nu toe consistent met de verwachtingen van het Standaardmodel, maar we weten dat het Standaardmodel er niet in slaagt om een groot aantal experimentele waarnemingen te verklaren, wat ons motiveert om verder onderzoek te doen en metingen met hogere precisie uit te voeren.

De aanzienlijke toename van hoeveelheid gegevens tijdens de Run 2 gegevensverzamelingsperiode van 2015 tot 2018 opende de deur naar een precisietijdperk van Higgs-bosonfysica, waarin een overvloed aan eerder statistisch beperkte metingen kon worden uitgevoerd en de nauwkeurigheid van de metingen aan eigenschappen als massa en koppelingen kon worden verbeterd. De totale vervalbreedte, die gerelateerd is aan de vervaltijd van het Higgs-boson, is een eigenschap die buiten het experimentele bereik lag die met de Run 1 dataset kon worden bereikt. De Run 2 dataset maakte het mogelijk om deze eigenschap wel te bepalen via verschillende experimentele

technieken, waarvan er één is door de meting van quantuminterferentie-effecten in het $H \rightarrow \gamma\gamma$ vervalkanaal, zoals hieronder zal worden beschreven.

De vervaltijd van de Higgs-boson

Weinig deeltjes in de natuur zijn echt stabiel, zoals het elektron en het foton. De rest zijn instabiel en vervallen via specifieke vervalkanalen, of *modi*, naar andere deeltjes. De levensduur, τ , van een instabiel deeltje is omgekeerd evenredig met de totale vervalbreedte, Γ , die wordt gedefiniëerd als de som van alle toegestane partiële vervalkanalen, i :

$$\tau = \frac{\hbar}{\Gamma}, \quad \text{where } \Gamma = \sum_{i=0}^n \Gamma_i. \quad (8.4)$$

Voor een fundamenteel deeltje komt de totale vervalbreedte overeen met de breedte van de verdeling van de invariante massa. Voor een Higgs-boson met een massa van rond de 125 GeV is de theoretische voorspelling voor de totale vervalbreedte [3]:

$$\Gamma_H^{\text{SM}} = 4.09 \pm 0.16 \text{ MeV}. \quad (8.5)$$

Omdat de totale vervalbreedte wordt gedefiniëerd door het optellen van alle partiële vervalkanalen, zou het bestaan van een nieuw, onvoorspeld Higgs-boson vervalkanaal de waarde van Γ_H veranderen. Als een donker materiedeeltje koppelt aan de Higgs-boson, zou dit bijvoorbeeld het aantal toegestane vervalkanalen verhogen, wat resulteert in een grotere dan verwachte totale vervalbreedte. Om deze reden is de vervalbreedte van het Higgs-boson een ideale probe voor nieuwe fysica, en het nauwkeurig meten van deze parameter is dan ook van het grootste belang omdat het een aanwijzing kan geven voor het bestaan van fysica buiten het Standaardmodel.

Het Higgs-boson bij de LHC

De Large Hadron Collider (LHC) bevindt zich bij het *Conseil Européen pour la Recherche Nucléaire* (CERN) in Genève, Zwitserland. De ATLAS-detector bevindt zich op een van de vier interactiepunten rondom de 27 kilometer lange LHC-ring; de CMS-, LHCb- en ALICE-detectors bevinden zich op de andere drie punten, elk met hun eigen fysicadoelen en dus met hun eigen detectorontwerp. De ATLAS-detector kun je zien als een enorme camera die *foto's* maakt van de deeltjes die in de botsingen worden geproduceerd. Deze botsingen vinden plaats tussen groepen botsende protonen, waarbij de botsende groepen bekend staan als een *bunch*; één bunch bevat 10^{11} protonen die reizen met een snelheid van 99.9999990% van de lichtsnelheid en in de botsing is er een energie van 7 TeV in 2010 tot 13.6 TeV in 2024. Aangezien het proton geen fundamenteel deeltje is, vinden de botsingen eigenlijk plaats tussen de bestanddelen van het proton; ofwel de quarks of gluonen die het proton vormen. Het diagram in Figuur 8.7 toont deze aard van proton-proton

(pp) botsingen bij de LHC.

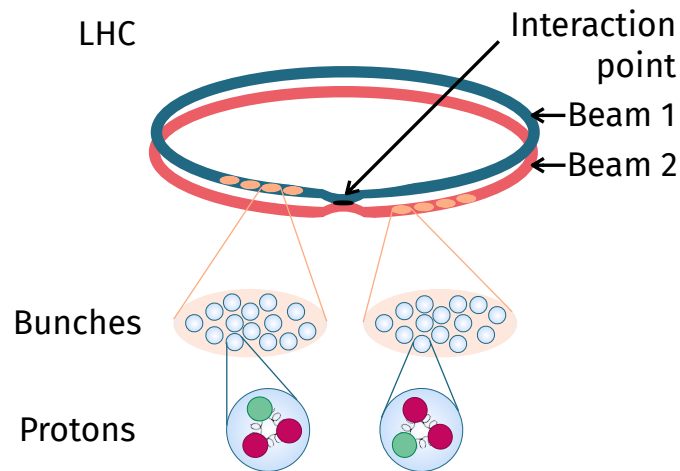


Figure 8.7: Overzicht van proton-proton botsingen bij de LHC. Protonen worden in bunches, die elk 10^{11} protonen bevatten, versneld in de LHC-ring en vervolgens in botsing gebracht op een aantal punten in de ring. Botsingen vinden plaats tussen de quarks en gluonen, de bouwstenen van de individuele protonen.

De gegevensverzamelingsperiode van Run 2 vond plaats bij een botsingsenergie van $\sqrt{s} = 13$ TeV. Bij deze energie is de dominante productie van de Higgs-boson, voor een Higgs-boson met een massa van $m_H = 125$ GeV, door twee gluonen die annihileren, wat bekend staat als gluon-gluon fusie (ggF). Zodra een Higgs-boson is geproduceerd, vervalt deze, zoals eerder vermeld, na gemiddeld slechts 1.6×10^{-22} seconden via een van de vele mogelijke vervalkanalen. Het dominante vervalkanaal voor een Higgs-boson met een massa van rond 125 GeV is $H \rightarrow b\bar{b}$, wat ongeveer 58% van de tijd gebeurt. Omdat het Higgs-boson koppelt aan massa, is er in het Standaardmodel geen directe interactie tussen het Higgs-boson en een massaloos deeltje, zoals bijvoorbeeld het foton. Het $H \rightarrow \gamma\gamma$ vervalkanaal verloopt daarom via een virtuele loop met massieve deeltjes en is daarom sterk onderdrukt, waardoor deze slechts 0,2% van de totale vervalsmogelijkheden vormt [3].

De ATLAS-detector meet de eigenschappen van het Higgs-boson door de deeltjes te detecteren die worden geproduceerd in pp botsingen. Deze doorkruisen de detectorlagen en laten *hits* achter in de vorm van energiedeposities. Het binnenste deel van ATLAS is de Inner Detector, een detectiesysteem van silicium en gasdetectoren dat gebruikt wordt om de banen (tracks) en vervallocaties (vertices) van elektrisch geladen deeltjes te meten. Een magnetisch veld van 2 T omringt de Inner Detector, waardoor de gemeten banen van geladen deeltjes gekromd zijn. De straal van deze kromming maakt het vervolgens mogelijk om de impuls van het deeltje te bepalen. Naar buiten toe is de volgende subdetector de elektromagnetische calorimeter, die verantwoordelijk is voor het meten van energie die wordt gedeponereerd door elektromagnetische spoeiers van

elektronen en fotonen, gevolgd door sproeiers veroorzaakt door hadronen zoals protonen en neutronen, die worden gemeten door de hadronische calorimeters. Het laatste subdetector-systeem is de muonspectrometer die, samen met de Inner Detector, de sporen meet die muonen achtergelaten terwijl ze de detector doorkruisen. De muonspectrometer is ondergedompeld in een toroïdaal magnetisch veld van 4 T, waardoor de banen van de muonen gebogen zijn. Omdat protonenbundels elke 25 ns botsen, een botsingsfrequentie van 40 MHz, geeft een totale hoeveelheid data van ongeveer 40 TB per seconde. Een reeks triggersystemen, zowel online als offline, is nodig om deze datastroom te verminderen tot een meer beheersbare omvang. Uiteindelijk wordt ongeveer 1,5 GB data per seconde permanent opgeslagen en gebruikt voor fysica-analyse.

De ATLAS-detector wordt sinds 2011 gebruikt om de eigenschappen van het Higgs-boson in het $H \rightarrow \gamma\gamma$ vervalkanaal te bestuderen; dit was een van de twee kanalen die werden gebruikt voor de ontdekking, het andere kanaal was $H \rightarrow ZZ^* \rightarrow \ell^-\ell^+\ell^-\ell^+$, waarbij $\ell = e, \mu$. Ondanks de relatief lage vervalwaarschijnlijkheid heeft het $H \rightarrow \gamma\gamma$ kanaal een unieke experimentele signatuur doordat het twee duidelijke elektromagnetische sproeiers achterlaat, die overeenkomen met de twee fotonen, in de elektromagnetische calorimeter. Dit is ondanks het feit dat de werkzame doorsnede voor dit proces verschillende ordes van grootte lager is dan die van de dominante achtergrondprocessen van niet Higgs-boson processen, zoals geïllustreerd in Figuur 8.8. Om de experimentele gevoeligheid te vergroten moeten specifieke selectiecriteria worden toegepast op de data om het aantal signaal-event te maximaliseren en tegelijkertijd bijdragen van achtergrond te verminderen.

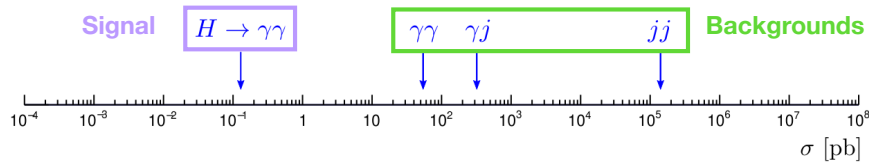


Figure 8.8: De werkzame doorsnede (cross-section) voor het signaal $H \rightarrow \gamma\gamma$ vervalkanaal is significant lager dan die van de drie dominante bronnen van achtergronden afkomstig van andere Standaardmodel processen: $\gamma\gamma$, γ -jet, en jet-jet production.

Interferometrie in het $H \rightarrow \gamma\gamma$ verval

Dit proefschrift beschrijft de bepaling van de breedte van het Higgs-boson door gebruik te maken van het $H \rightarrow \gamma\gamma$ vervalkanaal. De meest intuïtieve manier om de breedte van het Higgs-boson te meten zou zijn om rechtstreeks de breedte van de invariant massaverdeling van het Higgs-boson te meten, die in dit specifieke kanaal overeenkomt met de diphoton invariant massaverdeling, $m_{\gamma\gamma}$. Deze grootheid is gedefiniëerd in termen van de energieën en de hoek, θ , tussen de twee fotonen als:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta)}, \quad (8.6)$$

waarbij E_1 en E_2 de energieën zijn van respectievelijk het meest energetische en het op een na meest energetische foton in de eindtoestand. De precisie van deze directe methode wordt sterk beperkt door de resolutie van de ATLAS-detector, die in de orde van 1 GeV [51] is (veel hoger dan de verwachte intrinsieke breedte van de verdeling, zoals vermeld in vergelijking 8.5). Dit is de reden dat er indirecte technieken moeten worden gebruikt; dit proefschrift richt zich op het benutten van een methode die effecten in de $m_{\gamma\gamma}$ invariant massaverdeling gebruikt die worden veroorzaakt door de aanwezigheid van interferentie in het $\gamma\gamma$ vervalkanaal. Quantuminterferentie doet zich voor tussen processen met dezelfde begintoestandsdeeltjes en eindtoestandsdeeltjes. In dit geval is het dominante signaal van het Higgs-boson $gg \rightarrow H \rightarrow \gamma\gamma$ dat interfereert met de achtergrondbijdrage zonder het Higgs-boson met $gg \rightarrow \gamma\gamma$. De Feynmandiagrammen van deze twee processen zijn te zien in Figuur 8.9.

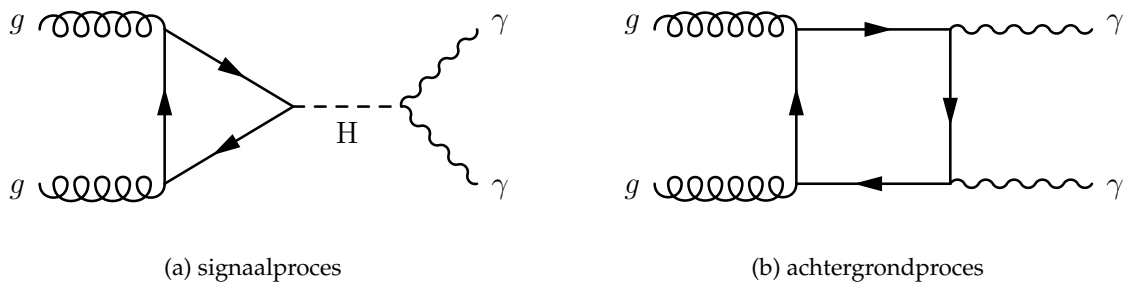


Figure 8.9: Feynmandiagrammen van het dominante productieproces van het Higgs-boson in het diphoton-vervalkanaal (signaalproces), $gg \rightarrow H \rightarrow \gamma\gamma$ (Figuur 8.9a) en het achtergrondproces, $gg \rightarrow \gamma\gamma$ (Figuur 8.9b).

De aanwezigheid van deze door gg -geïnduceerde interferentie op de invariant massaverdeling van het resonante signaal veroorzaakt allereerst een verstoring in de piek zelf. Dit komt door de vorm van de interferentie die, wanneer gecombineerd met het signaal, een verschuiving *massaverschuiving* veroorzaakt in positie van de piek in de verdeling naar lagere waarden van $m_{\gamma\gamma}$. De voorspelde grootte van deze massaverschuiving in het Standaardmodel is ongeveer 100 MeV op eerste orde precisie [40], wat afneemt tot ongeveer 70 MeV op een nauwkeurigheid van de volgende orde van de berekening [4]. Deze massaverschuiving is gerelateerd aan de breedte van het Higgs-boson, wat maakt dat een meting van de massaverschuiving een indirecte bepaling is van de breedte van het Higgs-boson, Γ_H . Deze relatie is te zien in Figuur 8.10, waar de theoretische afhankelijkheid is berekend voor verschillende ordes van precisie in de berekening.

De interferentiebijdrage veroorzaakt ook een vermindering van de totale werkzame doorsnede vergeleken met die van het verwachte signaal. Deze vermindering wordt voorspeld met een nauwkeurigheid van 1-2% [43, 44]. Naast de dominante gg -interferentie zijn er ook ondergeschikte effecten als gevolg van qg -geïnduceerde interferentie die ook van invloed zijn op de gemeten $m_{\gamma\gamma}$ -verdeling. Dit heeft een vergelijkbare vorm als de gg -interferentie, met de aantekening dat

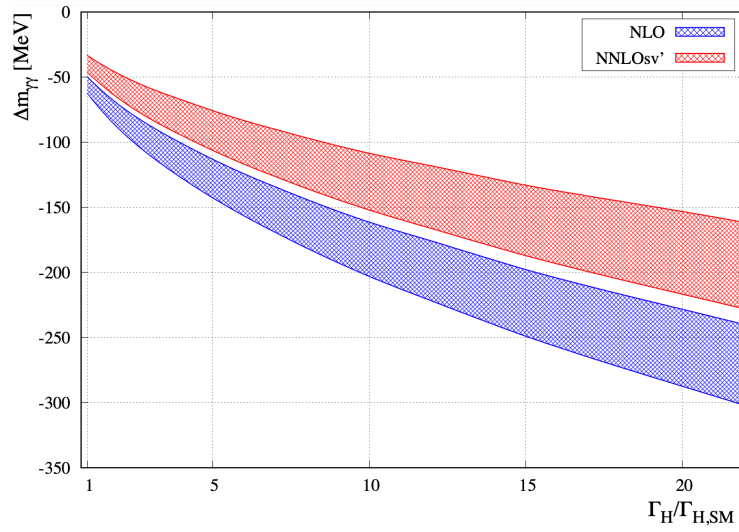


Figure 8.10: Massverschuiving, $\Delta m_{\gamma\gamma}$, als functie van de genormaliseerde breedte van het Higgs-boson in het Standaardmodel [41], die is berekend op nauwkeurigheid van next-to-leading orde (NLO) en nauwkeurigheid van de volgende volgende orde (NNLOsv'). De band beschrijft de theoretische onzekerheid.

de waargenomen piek- en dipstructuur omgekeerd is ten opzichte van de qg -interferentie, en dus juist een verschuiving naar hogere waarden van $m_{\gamma\gamma}$ veroorzaakt van ongeveer 30 MeV [45]. Als gevolg hiervan is de totale massaverschuiving, rekening houdend met zowel de gg - als qg -interferentie, ongeveer 30% minder dan wanneer alleen de gg -interferentie wordt meegenomen.

Om de experimentele gevoeligheid te verbeteren, worden gebeurtenissen verdeeld in twee *categorieën*, door een selectie te maken op de transversale impuls van het twee-fotonsysteem, $p_T^{\gamma\gamma}$. Categorie 1 wordt gedefinieerd door de eis $p_T^{\gamma\gamma} < 30$ GeV, terwijl categorie 2 gebeurtenissen bevat in het gebied $p_T^{\gamma\gamma} \geq 30$ GeV. Deze strategie is gebaseerd op het feit dat de werkzame doorsnede van de interferentie evenredig is met het kwadraat van het verschil van de signaal- en achtergrondamplitudes, en de verdeling van de signaal $p_T^{\gamma\gamma}$ een piek heeft bij lagere waarden, waardoor de effecten door interferentie naar verwachting dominant zijn in dit gebied. Deze keuze is gemaakt omdat het daarmee mogelijk wordt om de meting volledig uit te voeren in het $H \rightarrow \gamma\gamma$ vervalkanaal, wat kan leiden tot een gedeeltelijke wegvallen van experimentele systematische onzekerheden omdat er geen 'referentiemassa' (de Higgs-bosonmassa gemeten in een kanaal met weinig tot geen interferentie-effecten) vanuit een ander vervalkanaal hoeft te worden gebruikt.

Figuur 8.11a toont de $m_{\gamma\gamma}$ verdeling voor het resonante signaal en de gg -interferentie en qg -interferentiebijdragen, waarbij de interferentie is geschaald met een factor 10 voor visualisatiedoeleinden. Figuur 8.11b laat ook het resulterende effect op de $m_{\gamma\gamma}$ verdeling zien met behulp van gesimuleerde gebeurtenissen; rood is de verdeling voor het resonante signaal zelf en blauw laat

de gecombineerde signaal- en interferentieverdeling zien. Het relatieve verschil in de piekposities tussen deze twee verdelingen is 69,3 MeV.

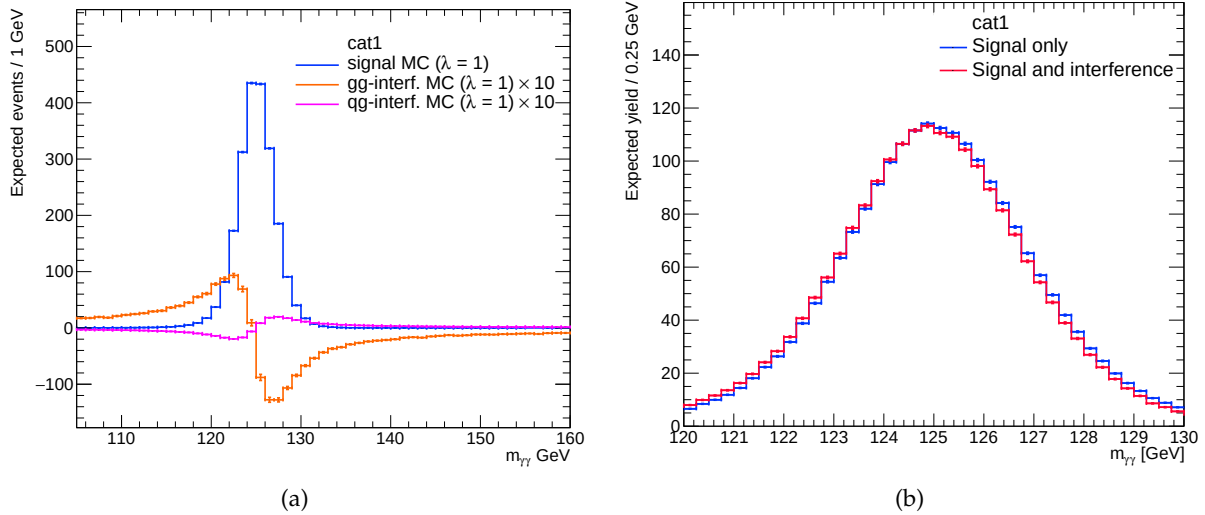


Figure 8.11: Invariante massa-verdelingen in het tweefoton-vervalkanaal in de analysecategorie gedefinieerd door $p_T^{\gamma\gamma} < 30$ GeV. Gesimuleerde gebeurtenissen zijn gebruikt om deze verdelingen te produceren. Figuur 8.11a toont de individuele verdelingen voor het resonante signaal en de gg -interferentie en qg -interferentieprocessen, waarbij de interferentie is geschaald met een factor 10. Figuur 8.11b laat de verwachte $m_{\gamma\gamma}$ verdeling zien voor het resonante signaalproces (rood), en de resulterende verdeling wanneer zowel het signaal als de interferentieprocessen zijn meegenomen (blauw).

Het meten van de $m_{\gamma\gamma}$ verdeling over het hele piekgebied, $120 < m_{\gamma\gamma} < 130$ GeV, maakt het mogelijk om zowel de vorm als de sterkte van het signaal te gebruiken om zo de breedte van het Higgs-boson te bepalen; de procedure die in dit proefschrift wordt gepresenteerd. Analytische functies worden gebruikt om elk van de signaal-, interferentie- en achtergrondbijdragen afzonderlijk te modelleren, die samen het gecombineerde model definiëren dat wordt gebruikt om de gegevens $m_{\gamma\gamma}$ verdeling te beschrijven. Het uiteindelijke model dat wordt gefit aan de waargenomen gegevens is te zien in Figuur 8.12 voor de twee categorieën die in de analyse worden gebruikt. Deze dataset komt overeen met $140,1 \text{ fb}^{-1}$ aan gegevens die door ATLAS zijn verzameld tijdens Run 2. Door een likelihoodfit van het gedefinieerde model aan deze gegevens uit te voeren, met zowel statistische als systematische onzekerheden, kan een limiet worden gezet op de totale vervalbreedte van het Higgs-boson, waarbij de waargenomen (verwachte) bovengrens voor de breedte van het Higgs-boson $\Gamma_H < 221,3 \text{ MeV}$ ($242,0 \text{ MeV}$) is op een betrouwbaarheidsniveau van 95%.

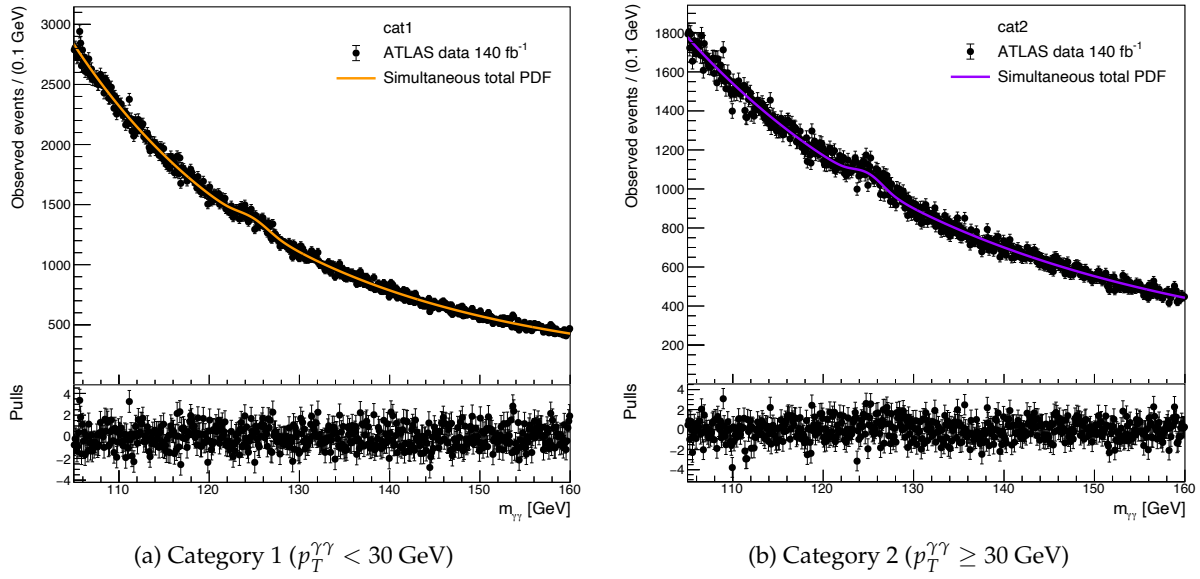


Figure 8.12: Invariante tweefoton-massaverdelingen in de ATLAS Run 2 dataset, waarbij de data in zwart wordt weergegeven en het totale signaal, interferentie en achtergrondmodel wordt weergegeven met de gekleurde. Figuur 8.12a toont de verdeling in categorie 1 die wordt gebruikt in de analyse ($p_T^{\gamma\gamma} < 30$ GeV), terwijl Figuur 8.12b overeenkomt met categorie 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

Toekomstperspectieven

De experimentele gevoeligheid voor de totale vervalbreedte van het Higgs-boson, Γ_H , die haalbaar is door gebruik te maken van interferentie-effecten, wordt voornamelijk beperkt door de statistische onzekerheid. Een meting met behulp van een grotere dataset zou een nauwkeurigere bepaling van Γ_H mogelijk maken. De High-Luminosity Large Hadron Collider (HL-LHC) is de geplande upgrade van de bestaande LHC naar een deeltjesversneller met een hogere luminositeit. De verwachte start is in 2029. Volgens verwachting zal de HL-LHC meer dan een tien jaar data verzamelen, waarin de ATLAS-detector naar verwachting 3000 fb^{-1} aan gegevens zal registreren. Als onderdeel van dit proefschrift is een projectie-studie uitgevoerd die laat zien dat een bovengrens voor de Higgs-boson breedte aan het einde van de HL-LHC als $\Gamma_H < 59,9 \text{ MeV}$ op een betrouwbaarheidsniveau van 95% kan worden verwacht. Deze uitkomst is geëxtrapoleerd vanuit het resultaat van de Run 2 analyse waarbij rekening is gehouden met een verminderde statistische onzekerheid, maar nog niet met mogelijke verbeteringen in de analysestrategie of verwachte verminderingen in de systematische onzekerheden. Het is daarom niet onrealistisch om te verwachten dat na de analyse van de dataset verzameld door ATLAS tijdens de HL-LHC periode, een meting van de Higgs-boson breedte met behulp van interferometrie haalbaar kan zijn.

Dit proefschrift presenteert de analyse van $H \rightarrow \gamma\gamma$ vervalprocessen die wordt gebruikt om de vervalbreedte van het Higgs-boson te bepalen door gebruik te maken van interferentie-effecten. Dit resultaat maakte het mogelijk om de breedte van het Higgs-boson te onderzoeken op een manier die complementair is aan andere bestaande experimentele methoden. Door de relatie

tussen de breedte van het Higgs-boson en de mogelijke vervalkanalen van het Higgs-boson, is het van vitaal belang om deze eigenschap te blijven onderzoeken, zodat nieuwe natuurkunde, waar het ook verborgen mag zijn, ontdekt kan worden.

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A | Event selection impact on the interference $m_{\gamma\gamma}$ distribution

The aim of this appendix is to investigate more closely the impact of the final diphoton selection applied during the event selection as described in section 6.3, which corresponds to the last row of the cutflow tables presented in section 6.3.2¹. In particular, the gg -interference is unique given the total cross-section for this process alone is negative, and the shape (similar for the qg -interference), contains a region of phase space with a negative number of expected events, and another region with a positive number of expected events. Figure A.1 displays a comparison between the $m_{\gamma\gamma}$ distribution before (in blue, labelled as ‘Rel. p_T cuts’ in the cutflow tables of section 6.3.2), and after (in pink) the $m_{\gamma\gamma} \in [105, 160]$ GeV selection has been applied.

The $m_{\gamma\gamma}$ distribution is asymmetric around 125 GeV, positive on one side, and negative on the other as is displayed in Figure A.1. For gg -interference at NLO (in orange), the negative peak is larger than the positive peak. So when the $m_{\gamma\gamma} \in [105, 160]$ GeV selection is applied, the impact on the total number of events either side of 125 GeV is not equal. The same is true also for the qg -interference process. Table A.1 compares the number of expected events in total, and below and above $m_{\gamma\gamma} = 125$ GeV, both before and after the $m_{\gamma\gamma} \in [105, 160]$ GeV selection. The number

Event selection applied up to	$m_{\gamma\gamma} < 125$ GeV	$m_{\gamma\gamma} \geq 125$ GeV	Total
Rel. p_T cuts	159.1	−224.1	−65.04
$m_{\gamma\gamma} \in [105, 160]$ GeV	132.5	−203.5	−71.01
Relative difference	20%	10%	8.7%

Table A.1: Number of expected in events in different regions of $m_{\gamma\gamma}$ phasespace, before and after applying the $m_{\gamma\gamma} \in [105, 160]$ GeV selection.

of events with $m_{\gamma\gamma} < 125$ GeV (positive yield) reduces by 20% with the $m_{\gamma\gamma}$ selection, while the number of events with $m_{\gamma\gamma} \geq 125$ GeV (negative yield) reduces by only 10%, resulting in larger

¹The results presented in this appendix use the h027 MxAODs.

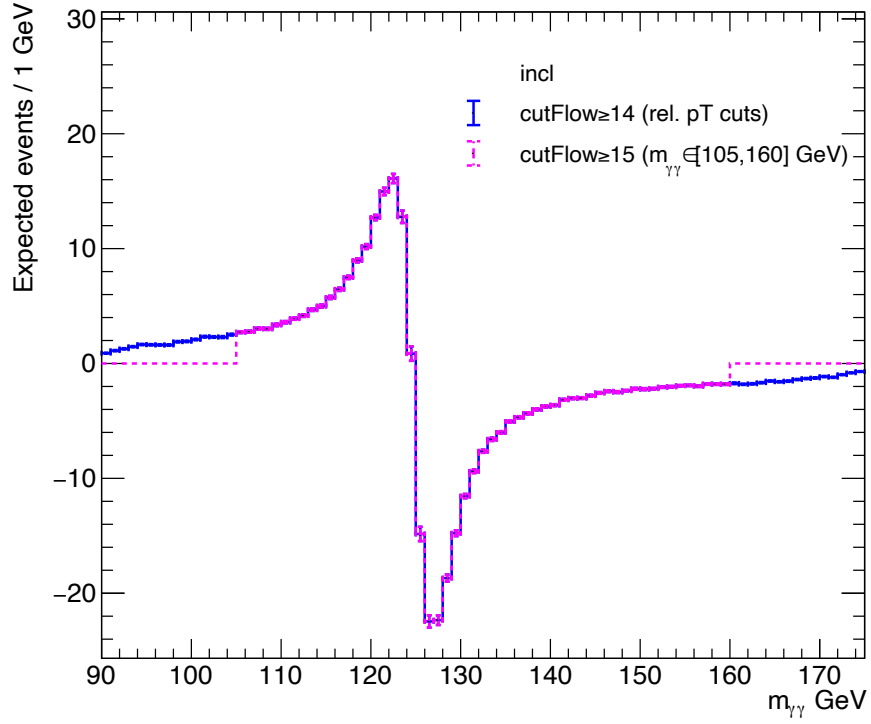


Figure A.1: Comparison between the inclusive diphoton invariant mass distribution when all event selections have been applied as per section 6.3 *except* the final $m_{\gamma\gamma}$ cut (in blue), versus the distribution obtained when also including the $m_{\gamma\gamma} \in [105, 160]$ GeV cut (in pink).

fraction of negative events present overall compared to before the $m_{\gamma\gamma}$ selection was applied. This explains the unintuitive behaviour of the final line in Table 6.6.

B | Impact of interference effects on the signal shape

To quantify the sensitivity to the Higgs boson width due to changes in the signal shape in addition to the interference effects, results from the following two model set-ups are compared:

1. Not allowing the signal shape to vary as a function of the Higgs boson width. Practically, this means fixing σ_{CB} to the value obtained when fitting the nominal SM signal MC sample (as per Table 6.10).
2. Allowing the signal shape to vary as a function of the Higgs boson width, σ_{CB} is parametrised in terms of λ according to: $\sigma_{CB}(\lambda) = \sigma_{CB}^{\text{SM}} + \alpha \times \lambda$. The parameter $\alpha = 0.001$ is extracted from the linear dependance between λ and the standard deviation of the corresponding signal MC distributions.

In each case the sensitivity to λ is estimated by taking the 95% upper limit obtained when scanning over the range $\lambda \in [0,200]$. These results are shown in Figure B.1, where the scan results shown in pink corresponds to setup number 1 listed above, and yellow is for setup number 2. The relative difference between the two upper limits on λ at the 95% confidence level is 0.2%. This result implies there is a really negligible impact on the sensitivity to the Higgs boson width when parametrising also the signal model in terms of λ , in addition to the interference component (the interference modelling strategy is described in section 6.6). For this reason, the signal dependance on the Higgs boson width can be safely ignored, as it brings no constraining power to the parameter of interest.

The advantage of the DSCB is that there is good separation between the contributions coming from the core, and from the tails, making it easier to apply systematic variations on the scale (on μ_{CB}) and on the resolution (to σ_{CB}). In the final statistical model, the only further alteration of the DSCB parameters is that μ_{CB} and σ_{CB} are each multiplied by a response function to take into account photon energy scale and photon energy resolution systematics respectively; this procedure will be described in section 6.8.1.

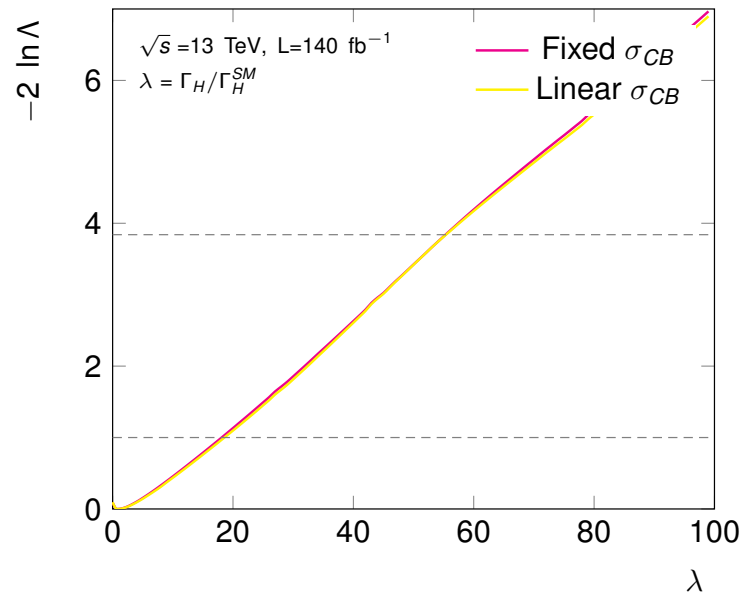


Figure B.1: Likelihood scan over the Higgs boson width parameterised by λ , considering two possible signal modelling strategies. The statistical fit has been performed on a simulated SM Asimov dataset.

C | Signal and interference kinematic distributions

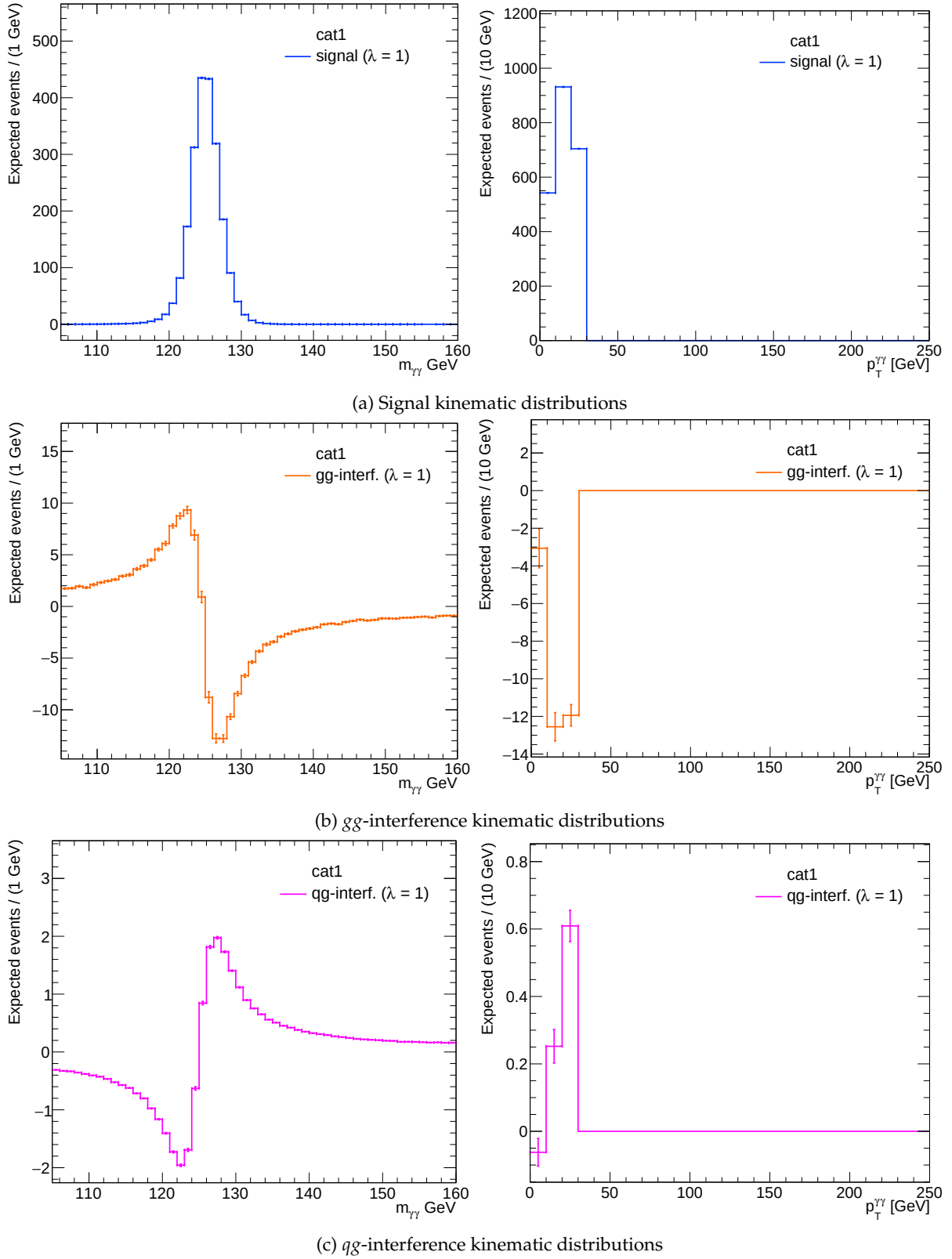
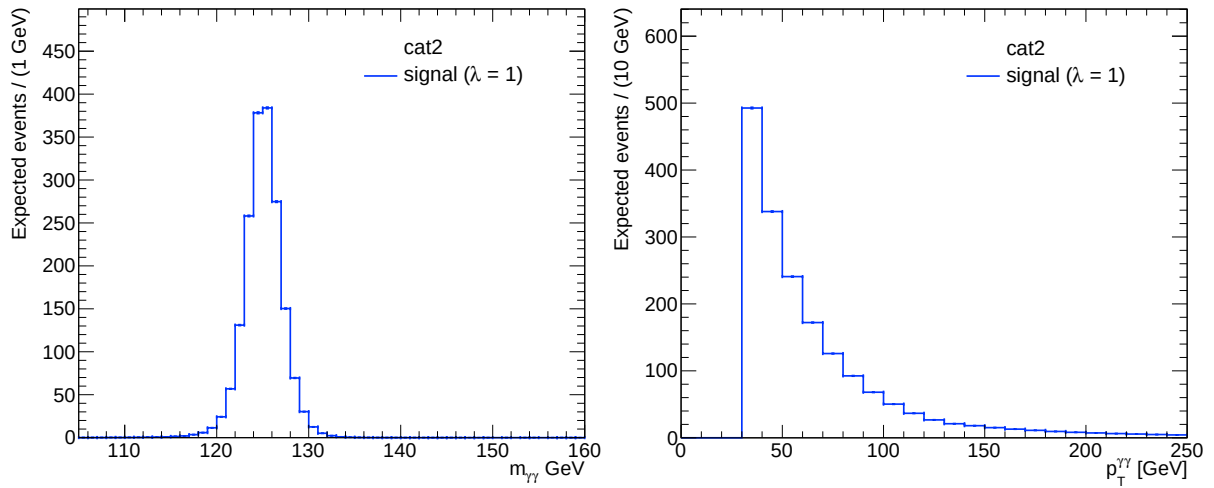


Figure C.1: Distributions of $m_{\gamma\gamma}$ and $p_T^{\gamma\gamma}$ for the signal and interference processes, after the diphoton event selection, in category 1 ($p_T^{\gamma\gamma} < 30$ GeV).



(a) Signal kinematic distributions

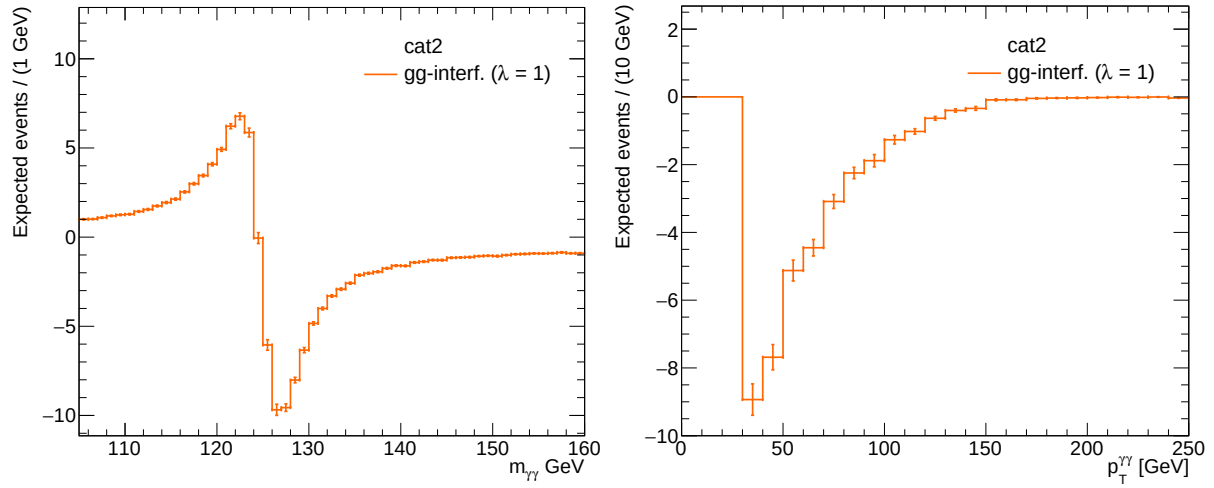
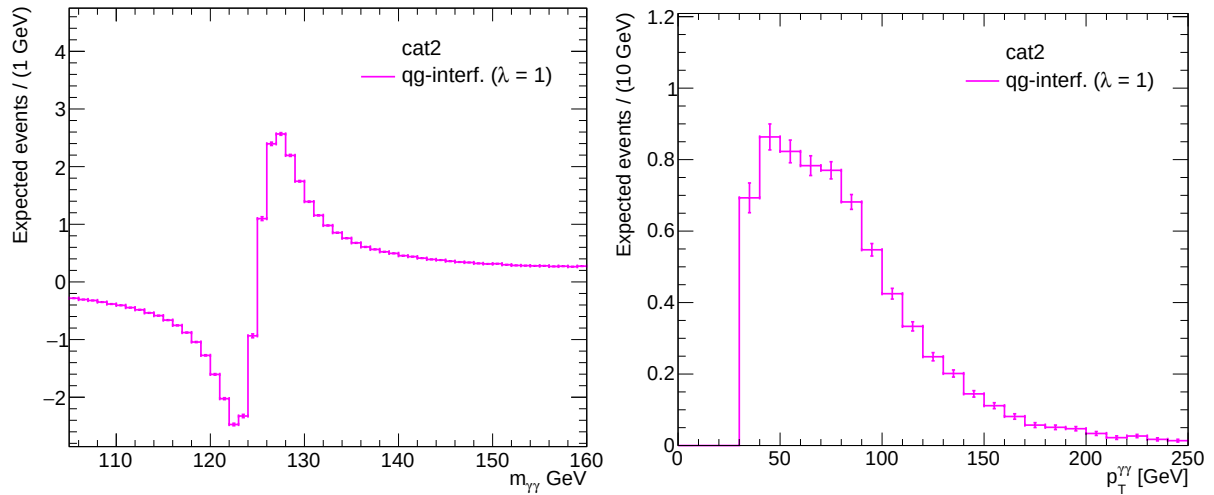
(b) gg -interference kinematic distributions(c) qg -interference kinematic distributions

Figure C.2: Distributions of $m_{\gamma\gamma}$ and $p_T^{\gamma\gamma}$ for the signal and interference processes, after the diphoton event selection, in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

D | Distributions required to define the interference morphing function

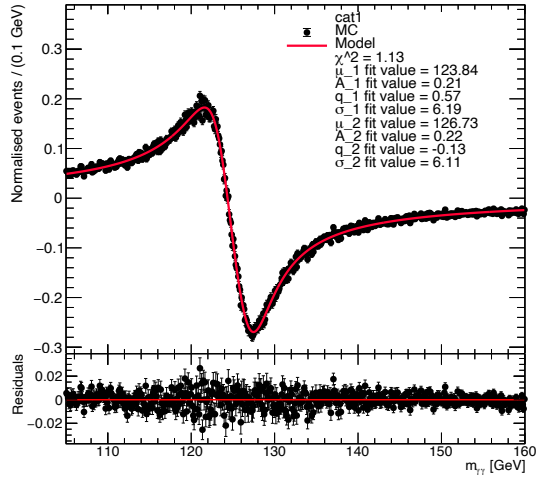
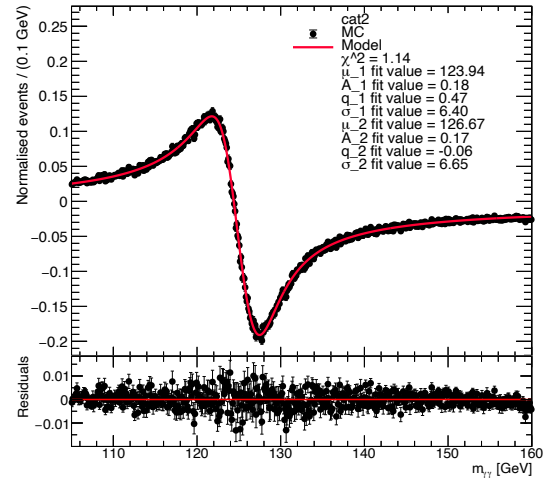
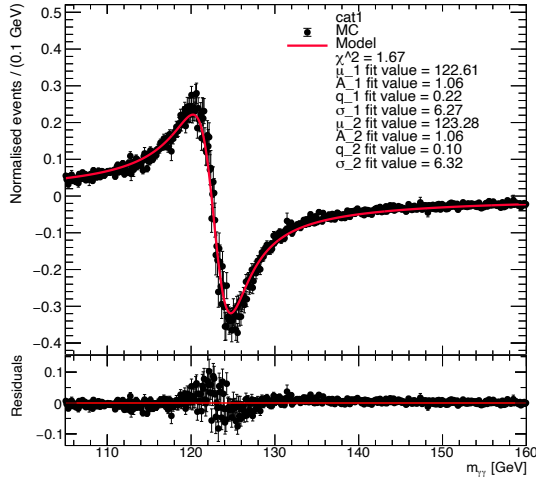
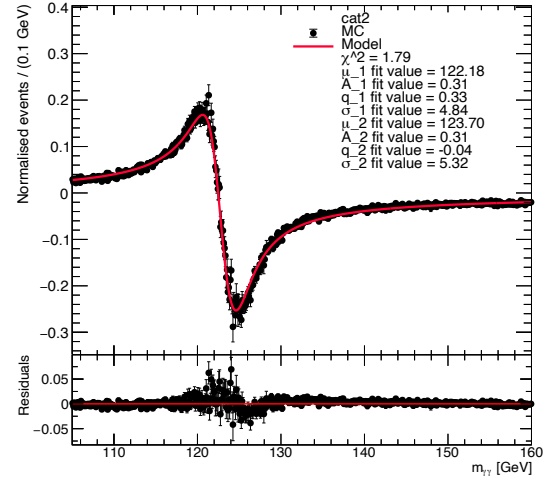
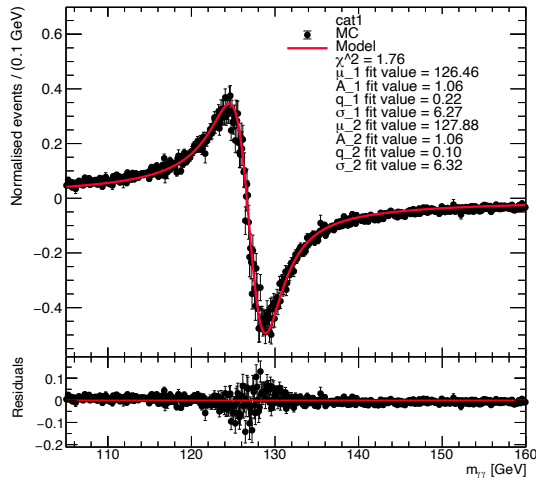
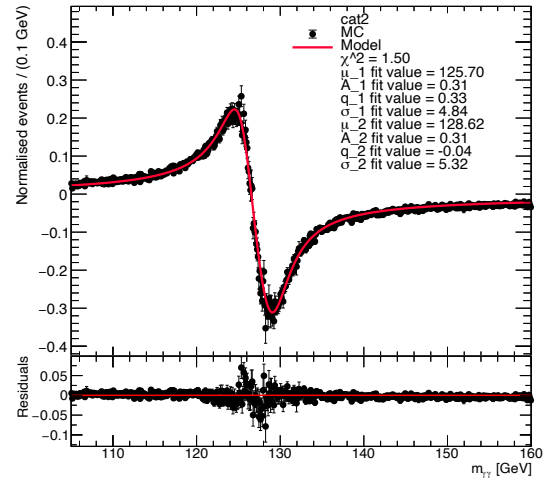
(a) Cat1, $m_H = 125$ GeV, $\lambda = 400$ (b) Cat2, $m_H = 125$ GeV, $\lambda = 400$ (c) Cat1, $m_H = 123$ GeV, $\lambda = 1$ (d) Cat2, $m_H = 123$ GeV, $\lambda = 1$ (e) Cat1, $m_H = 127$ GeV, $\lambda = 1$ (f) Cat2, $m_H = 127$ GeV, $\lambda = 1$

Figure D.1: Individual reference functions required to define a gg -interference star-morphing function that is continuously defined over $m_H \in [123 \text{ GeV}, 127 \text{ GeV}]$ and $\lambda \in [1, 400]$ values. Each reference function is plotted on top of the corresponding MC sample, where the specific m_H and λ are listed in the individual plot captions.

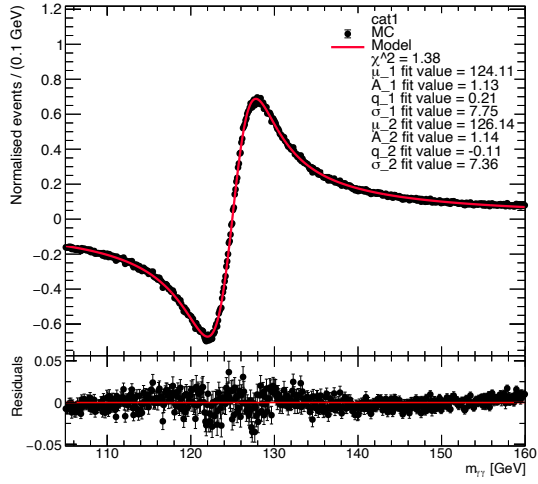
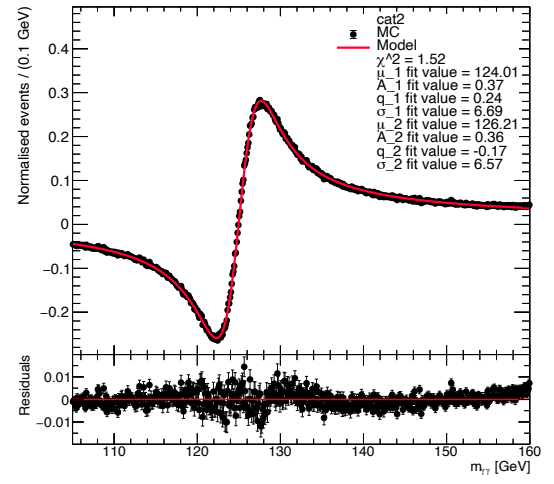
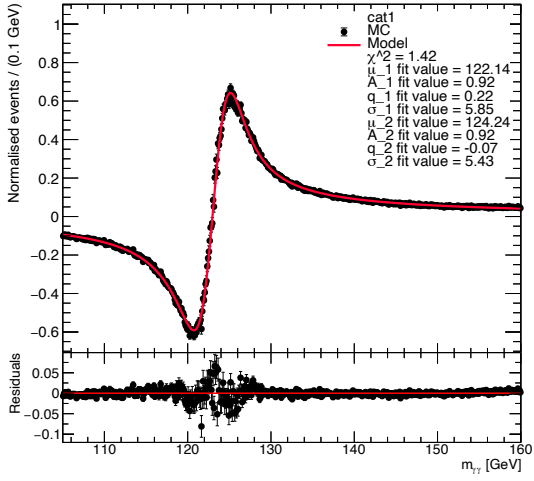
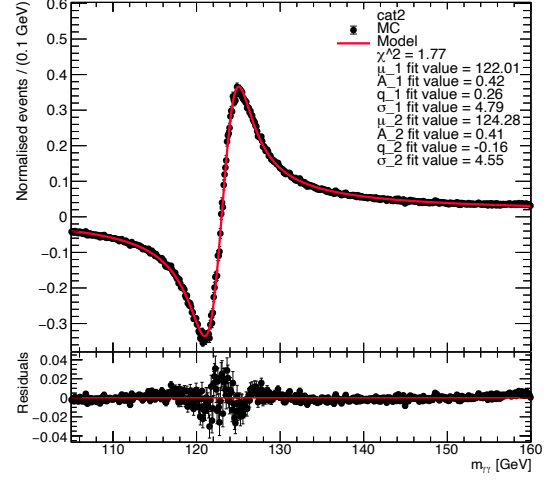
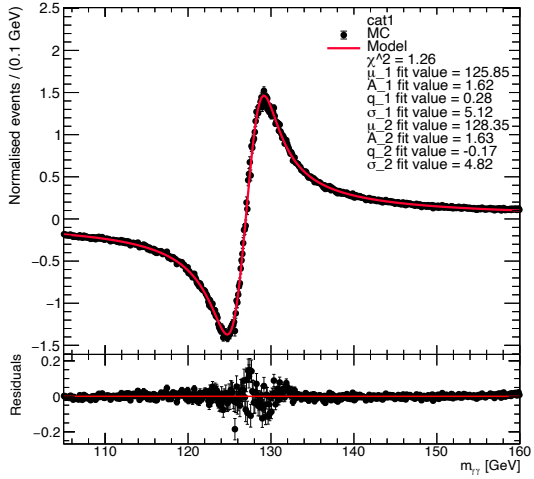
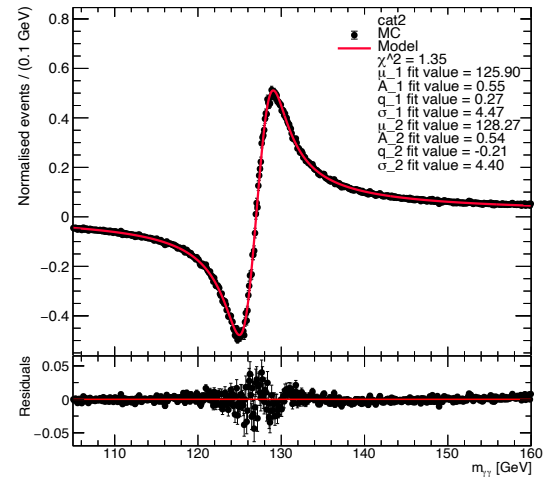
(a) Cat1, $m_H = 125$ GeV, $\lambda = 400$ (b) Cat2, $m_H = 125$ GeV, $\lambda = 400$ (c) Cat1, $m_H = 123$ GeV, $\lambda = 1$ (d) Cat2, $m_H = 123$ GeV, $\lambda = 1$ (e) Cat1, $m_H = 127$ GeV, $\lambda = 1$ (f) Cat2, $m_H = 127$ GeV, $\lambda = 1$

Figure D.2: Individual reference functions required to define a qg -interference star-morphing function that is continuously defined over $m_H \in [123 \text{ GeV}, 127 \text{ GeV}]$ and $\lambda \in [1, 400]$ values. Each reference function is plotted on top of the corresponding MC sample, where the specific m_H and λ are listed in the individual plot captions.

E | Additional distributions required for systematic uncertainties

E.1 Shape systematic uncertainties evaluated in category 2

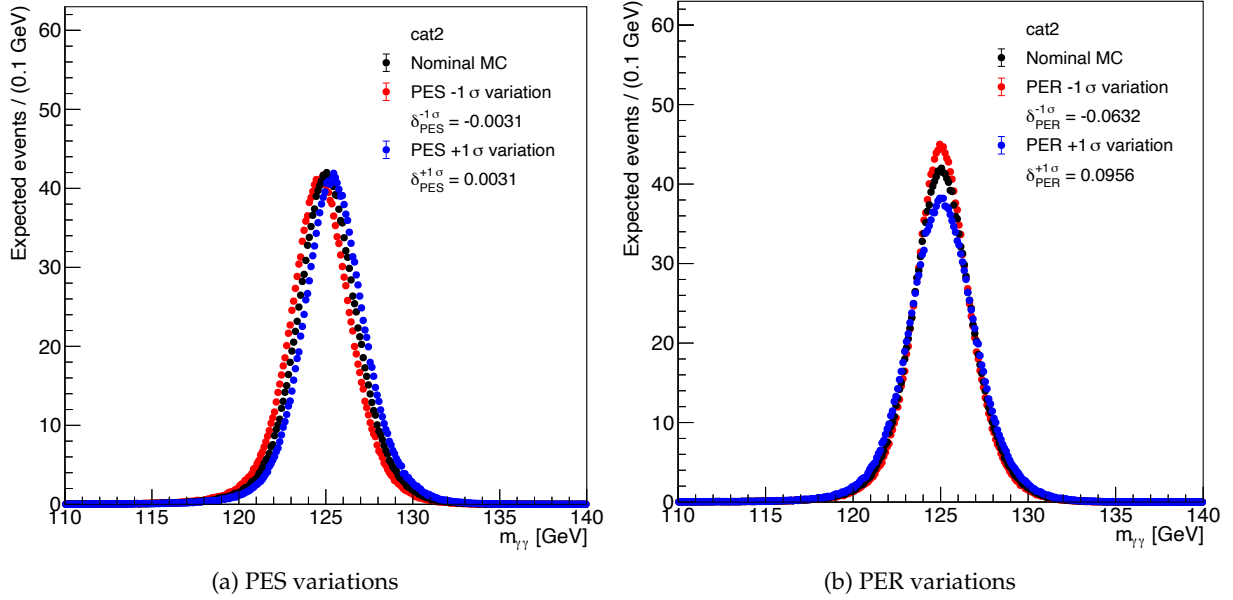


Figure E.1: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (E.1a) photon energy scale and (E.1b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the signal process in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

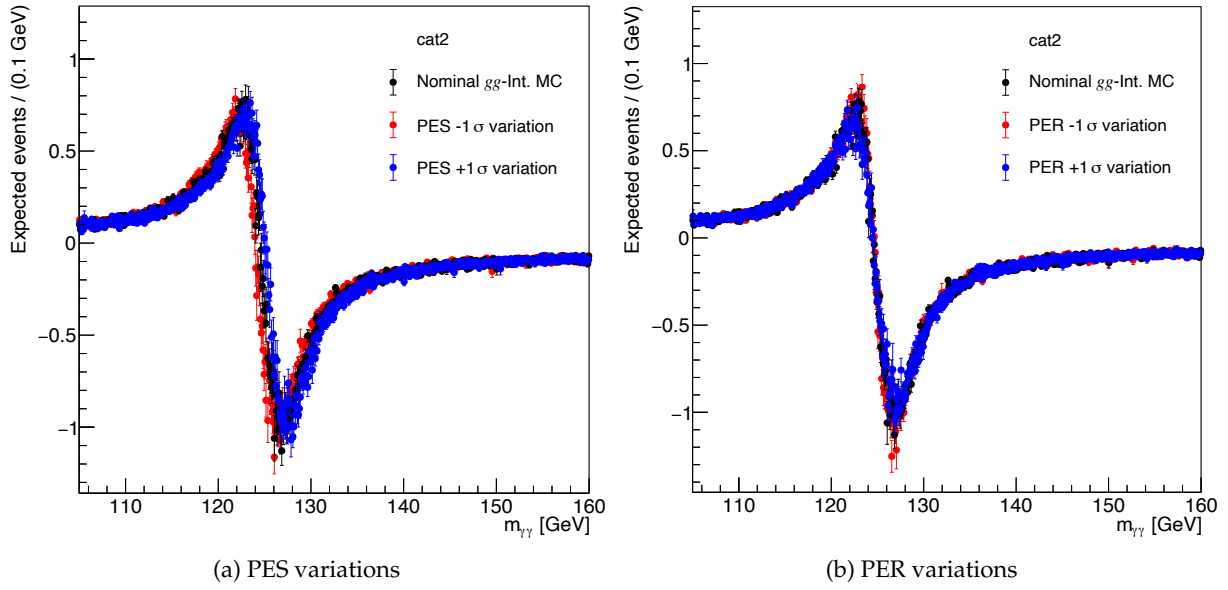


Figure E.2: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (E.2a) photon energy scale and (E.2b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the gg -interference process in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

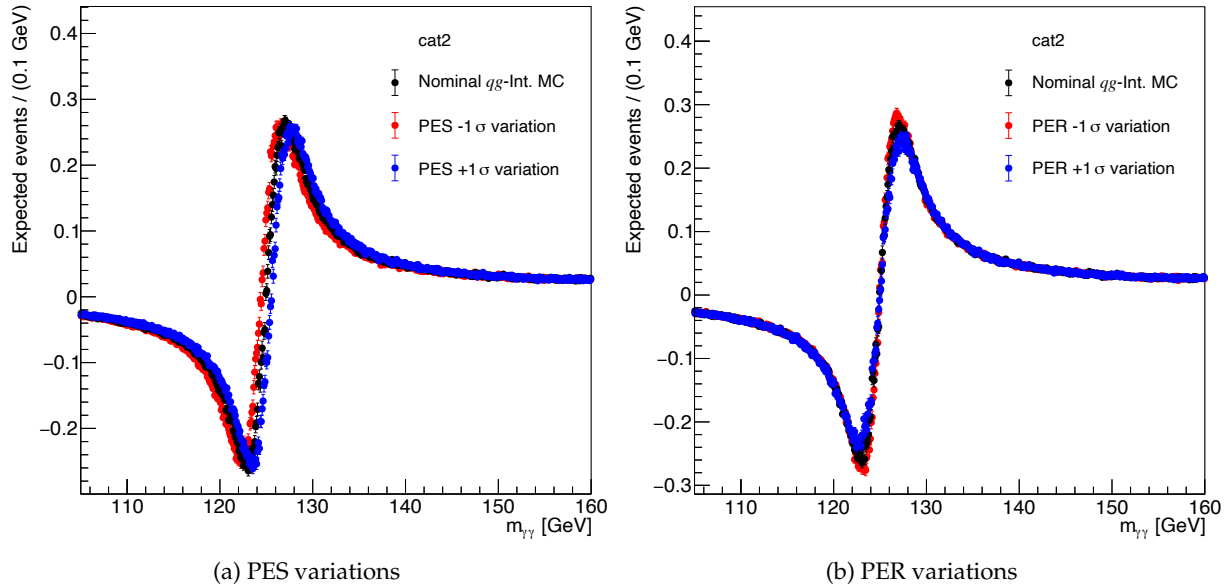


Figure E.3: Diphoton invariant mass distributions for the nominal, and $\pm 1\sigma$ (E.3a) photon energy scale and (E.3b) photon energy resolution, systematic uncertainty variations obtained using MC simulated events of the qg -interference process in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

E.2 Analytical functions describing the PES and PER interference systematic variations

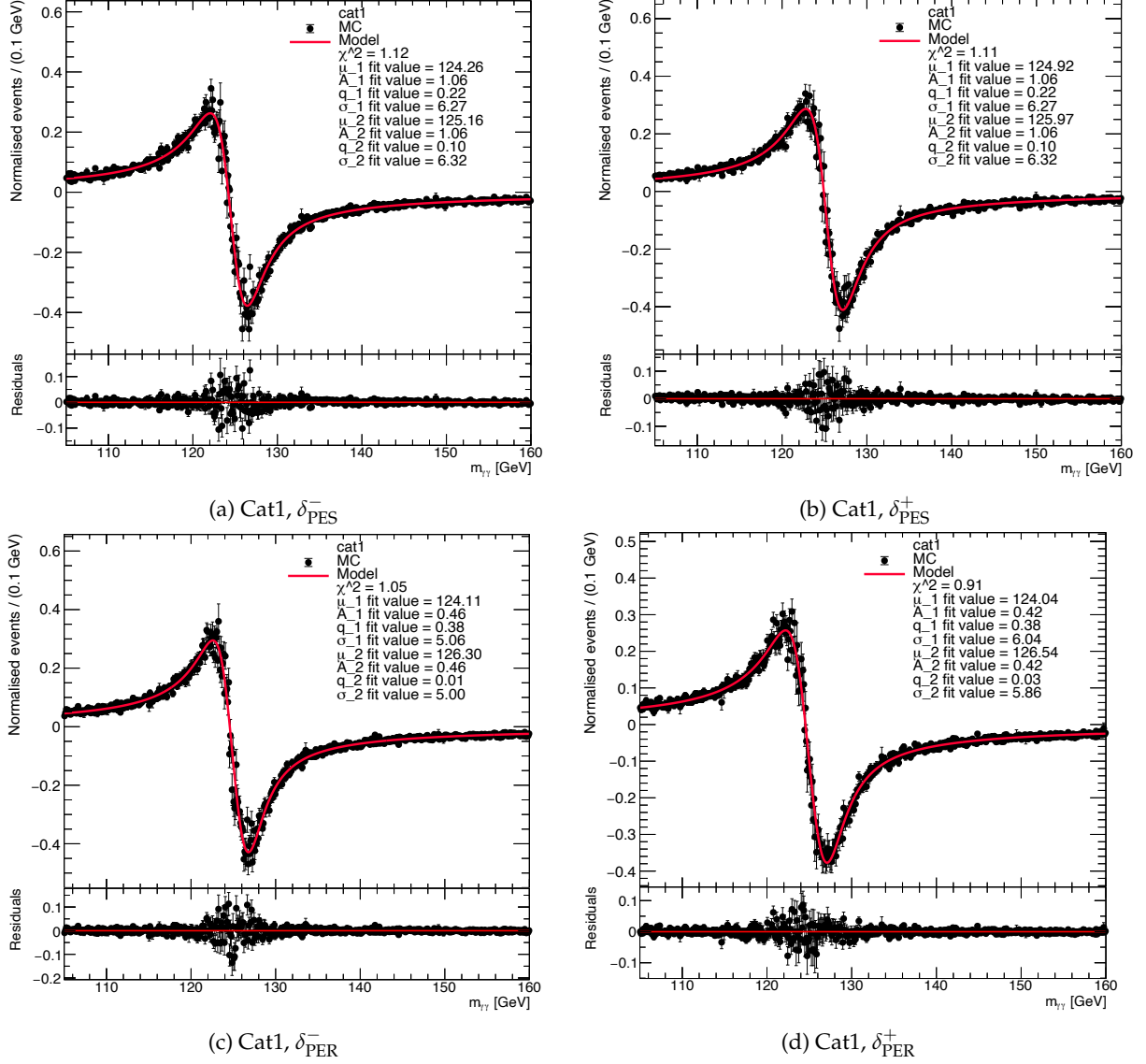


Figure E.4: Individual reference functions required to define the gg -interference star-morphing function including PES and PER shape systematic variations, for category 1 ($p_T^{\gamma\gamma} < 30$ GeV). In each case, the analytical interference function is fitted to the MC $m_{T\gamma}$ distribution, and the fit values obtained are listed in the upper right hand corner of each plot.

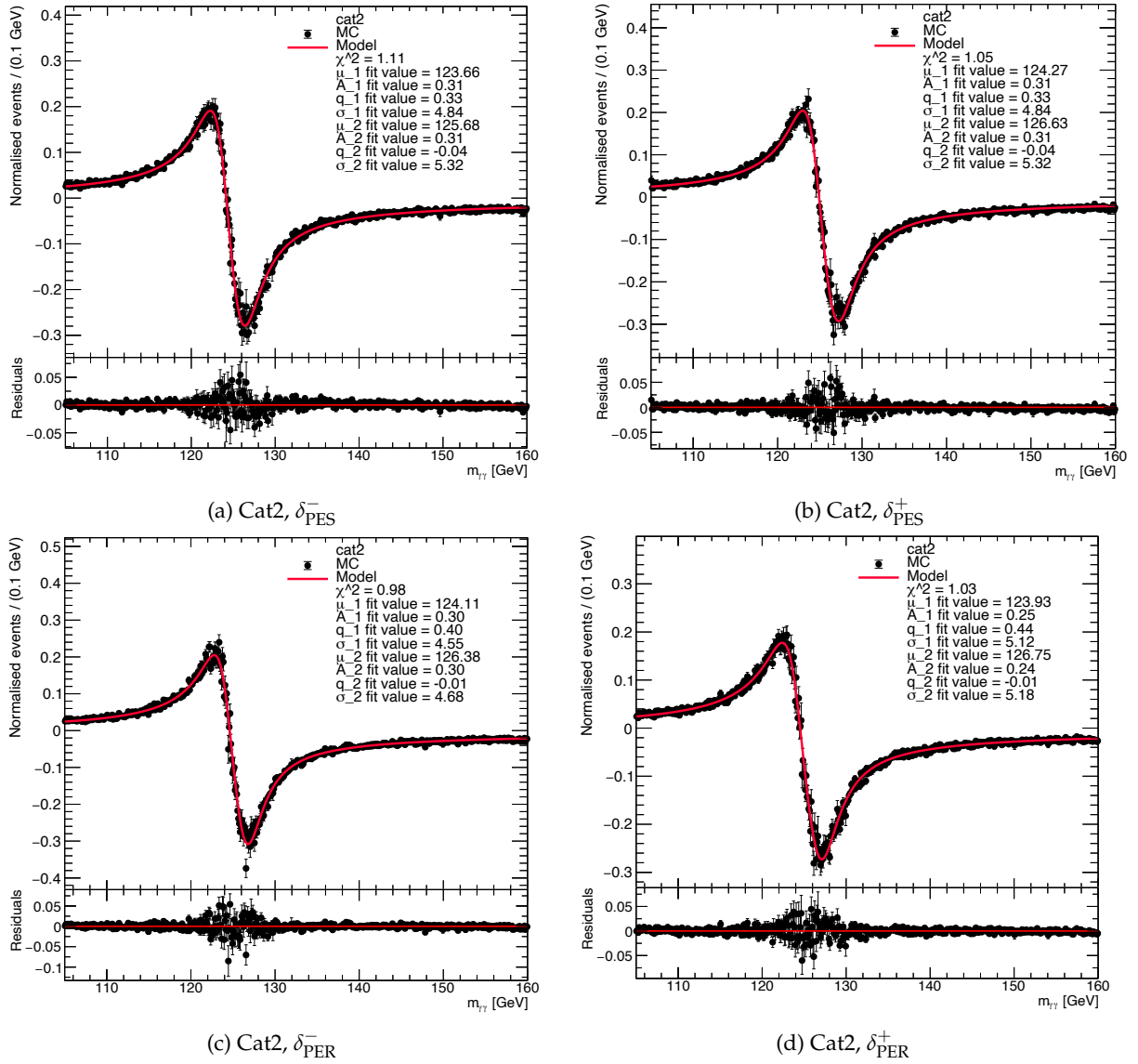


Figure E.5: Individual reference functions required to define the gg -interference star-morphing function including PES and PER shape systematic variations, for category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV). In each case, the analytical interference function is fitted to the MC $m_{\gamma\gamma}$ distribution, and the fit values obtained are listed in the upper right hand corner of each plot.

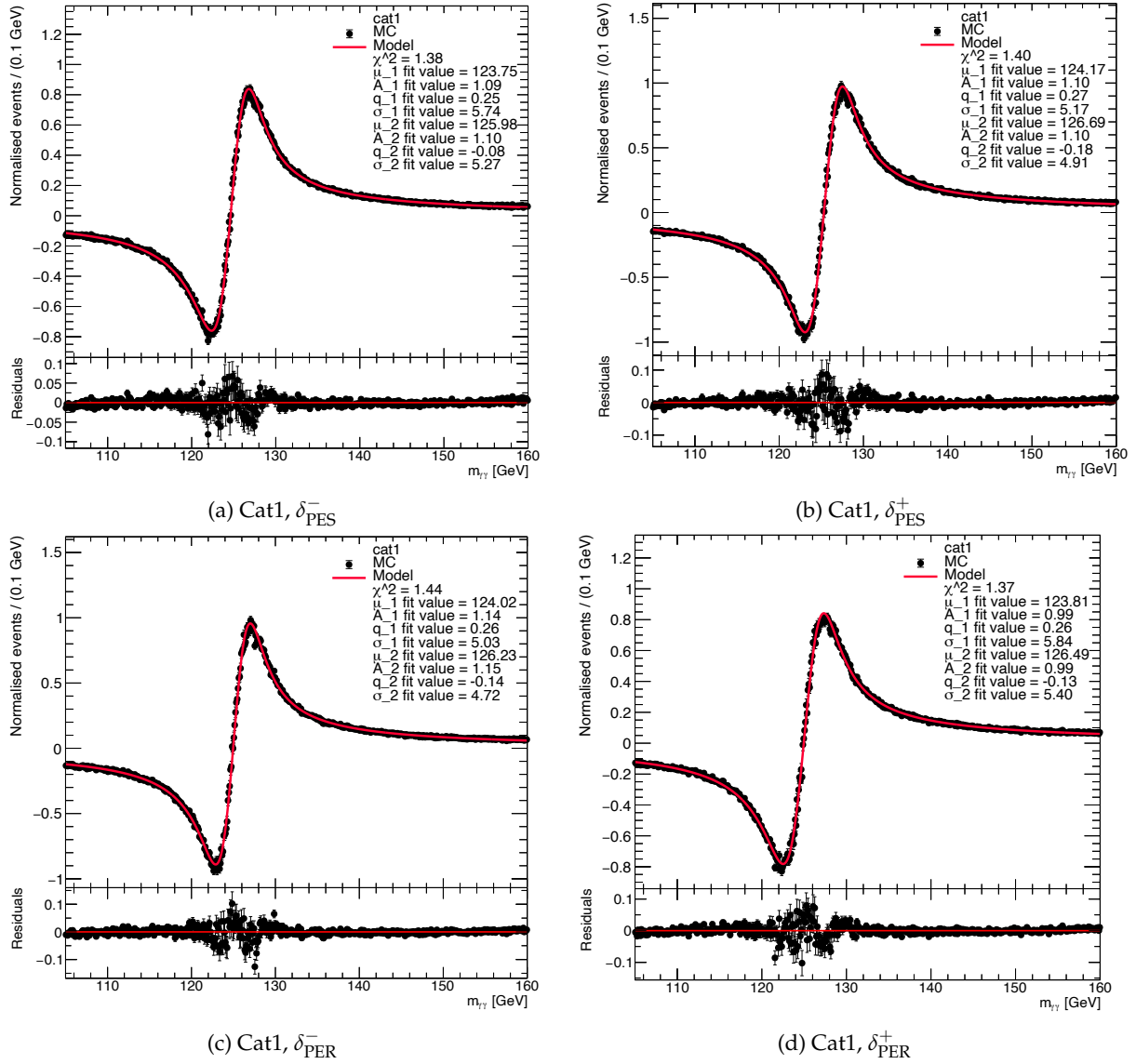


Figure E.6: Individual reference functions required to define the qg -interference star-morphing function including PES and PER shape systematic variations, for category 1 ($p_T^{\gamma\gamma} < 30$ GeV). In each case, the analytical interference function is fitted to the MC $m_{\gamma\gamma}$ distribution, and the fit values obtained are listed in the upper right hand corner of each plot.

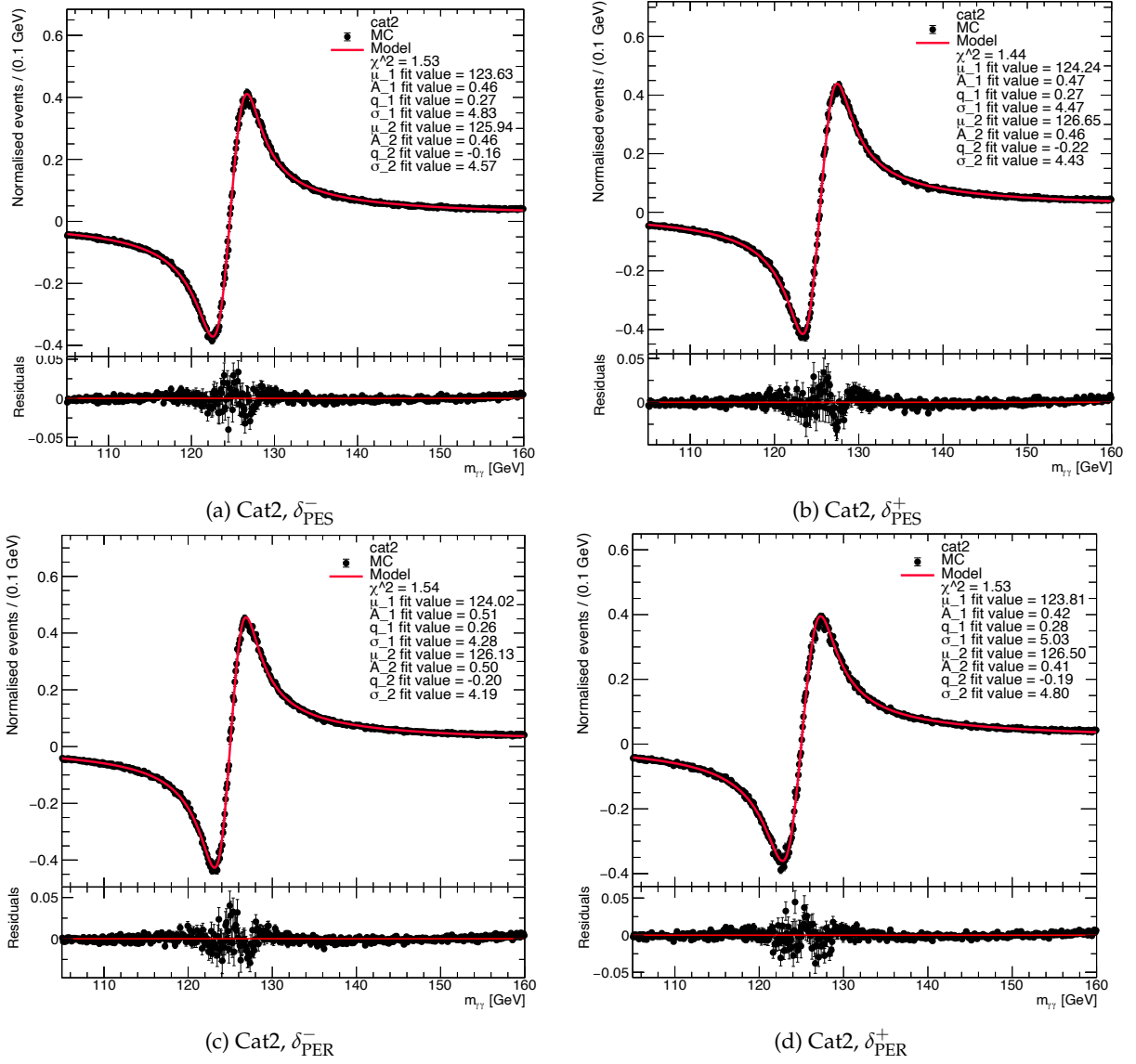


Figure E.7: Individual reference functions required to define the qg -interference star-morphing function including PES and PER shape systematic variations, for category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV). In each case, the analytical interference function is fitted to the MC $m_{\gamma\gamma}$ distribution, and the fit values obtained are listed in the upper right hand corner of each plot.

E.3 Evaluate interference morphing functions in category 2 used for the analysis

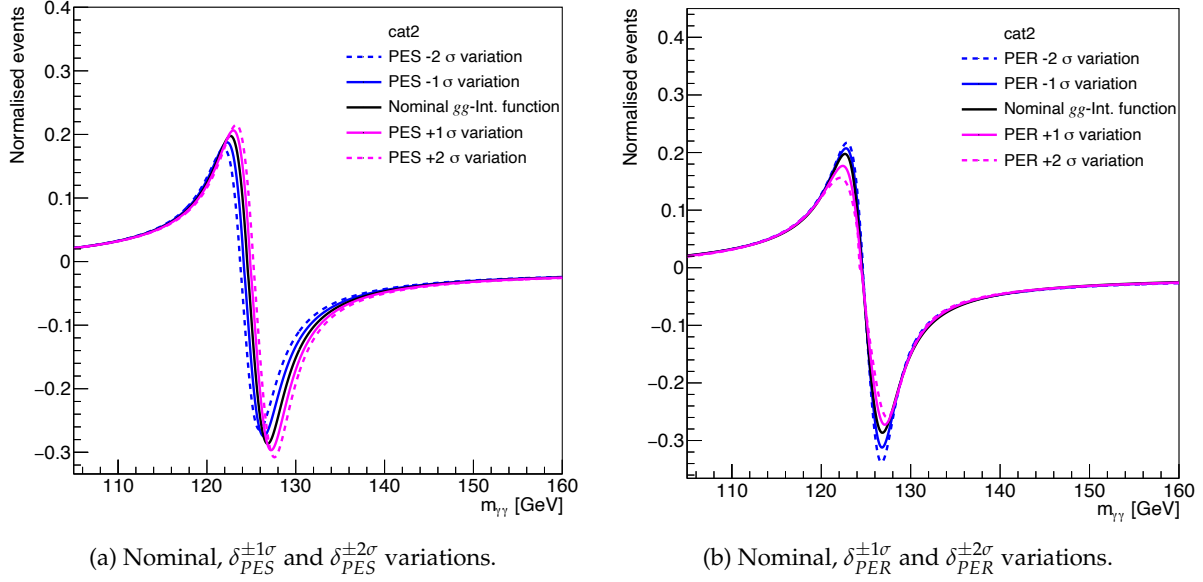


Figure E.8: Diphoton invariant mass distributions for the star-morphed gg -interference functions evaluated at the nominal value, as well as four systematic variations for the PES systematic (E.8a), and the PER systematic (E.8b) in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

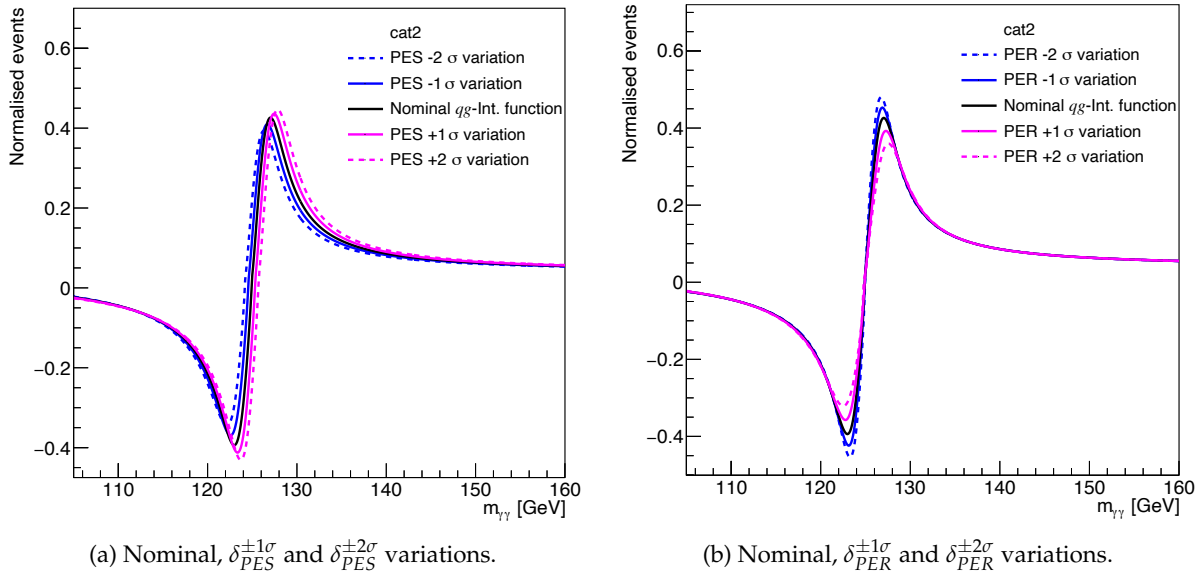


Figure E.9: Diphoton invariant mass distributions for the star-morphed qg -interference functions evaluated at the nominal value, as well as four systematic variations for the PES systematic (E.9a), and the PER systematic (E.9b) in category 2 ($p_T^{\gamma\gamma} \geq 30$ GeV).

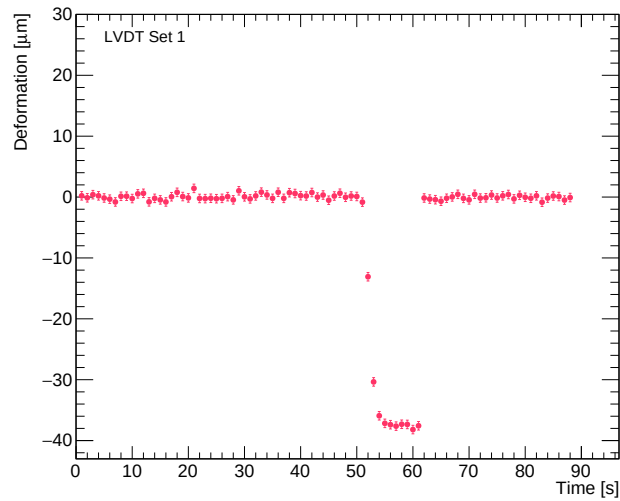
F | LVDT measurement validation tests

F.1 LVDT measurement validation

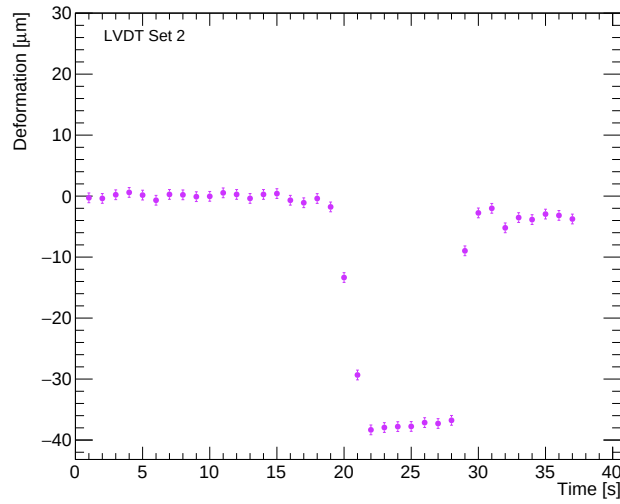
It is evident that the LVDT system performs (statistically) precisely in a static environment. To validate the deformation results measured by the LVDTs, the following question was posed. If the rings were manually deformed by a known amount, does the deformation measured by the LVDT coils match the known deformation? To answer this question, the subsequent test was undertaken, with each LVDT set being tested separately. A dial gauge was positioned with the needle on the top surface of the upper ring, directly above where the primary coil is mounted. Force was applied to the upper ring manually. Simultaneously, the deformation was measured by the dial gauge, and the LVDT coils recorded the change in voltage as a result of the mechanical deformation. The results of this measurement validation check are shown in Table F.1, and the output of the LVDT sets are shown in Figure F.1a - F.1c. Here the results have directly been converted to a relative displacement, rather than the output voltage recorded by the LVDT system. The results obtained indicate the LVDT measurements are indeed valid, and the deformation recorded does correspond to the actual deformation of the mock-up structure.

LVDT set	Dial gauge reading [μm]	LVDT measured deformation [μm]
1	-35 ± 3	-37.4 ± 0.7
2	-35 ± 3	-38.2 ± 2.1
3	-50 ± 3	-51.9 ± 3.6

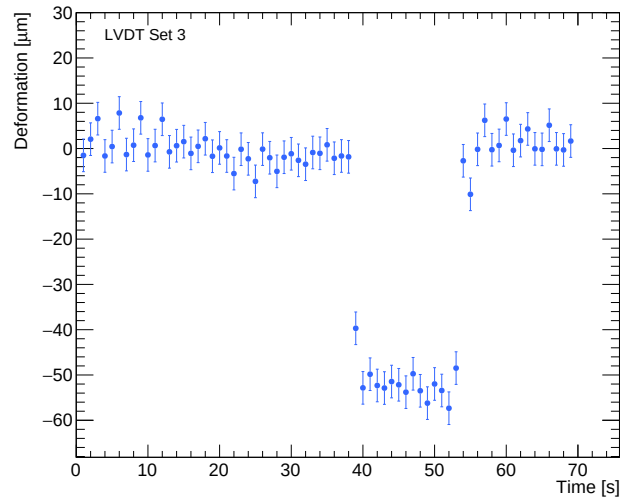
Table F.1: Validation results for the LVDT system. The second column displays the known deformation amount, as measured by the dial gauge. The third column presents the deformation amount as measured by the LVDT sets. In all cases, results are in strong agreement. The negative sign indicates that the distance between the upper and lower rings was reduced, i.e. the primary and secondary coils moved closer together.



(a)



(b)



(c)

Figure F.1: Relative deformation recorded by LVDT (F.1a) set 1, (F.1b) set 2, and (F.1c) set 3, during the LVDT measurement validation test. The statistical uncertainty on each point is ascribed as per the results of section 7.3.1.

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What a privilege it is to be in this position. Although my name is on the cover of this dissertation, I simply would not have reached this point without the guidance, support, wisdom, encouragement, and love of so many.

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