

Combined measurements of Higgs boson properties using $\sqrt{s} = 13$ TeV proton–proton collision data collected with the ATLAS detector

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利用 ATLAS 探测器累积大型强子对 撞机 13TeV 数据测量标准模型希格斯 玻色子产生截面和耦合参数

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ABSTRACT

In July 2012 the ATLAS and CMS collaborations announced the discovery of the Higgs boson with a mass of approximately 125 GeV using proton–proton collisions collected at center-of-mass energies $\sqrt{s} = 7$ TeV and 8 TeV at the Large Hadron Collider (LHC). It is one of the most significant achievements in physics and leads to the Nobel Prize in Physics in 2013.

Following the discovery of the Higgs boson, a broad range of measurements of its properties has been performed. To probe the Higgs sector in the Standard Model (SM) more deeply, it is important to have measurements of the Higgs productions, decay branching ratios and couplings with a higher precision by using more data accumulated in LHC Run 2 at $\sqrt{s} = 13$ TeV.

This dissertation presents my research in High Energy Physics at the LHC with the ATLAS experiment, including the measurements of the Higgs boson properties in the diphoton decay channel, and the measurement of the Higgs boson production and decay rates, as well as constraints on its couplings to SM particles by combining all available Higgs production modes and decay channels measured by ATLAS.

$H \rightarrow \gamma\gamma$ is one of the most important channels to study the property of Higgs boson. The measurements in this channel are performed with data collected in 2015 and 2016, corresponding to an integrated luminosity 36.1 fb^{-1} . 31 reconstructed categories are developed to maximize the sensitivity, to measure the inclusive production cross-sections-times-branching-ratio of $B(H \rightarrow \gamma\gamma)$ and the individual production processes: gluon–gluon fusion (ggF), vector-boson fusion (VBF), Higgs boson production in association with a vector boson (VH), and production of a Higgs boson in association with a top–antitop quark pair or a single top quark ($t\bar{t}H$ and tH). Results are also interpreted using the Simplified Template Cross Section framework (STXS) and the Higgs coupling strength framework (“ κ ”-framework). The inclusive signal strength in this channel is measured to be 0.99 ± 0.14 , with an improvement on precision at a level of 40% comparing to the ATLAS Run 1 result.

To further improve the precision of the Higgs property measurement, the combination of Higgs properties measurement employs inputs from many individual Higgs channels, including $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $VH(H \rightarrow bb)$, $H \rightarrow \tau\tau$, $ttH(H \rightarrow \text{Multi-Lepton})$, $ttH(H \rightarrow bb)$, $H \rightarrow \mu\mu$, $VBF(H \rightarrow bb)$, $H \rightarrow \text{invisible}$ and $H \rightarrow ZZ(\text{offshell})$, with integrated luminosity 24.5 - 79.8 fb⁻¹. After building a likelihood-based combination mechanism, the production cross sections, decay branching ratios, STXS and coupling strength results are measured. The global signal strength is $\mu = 1.11^{+0.09}_{-0.08}$. The Higgs coupling strength results are with improvements on precision from 20% to 30% comparing to the ATLAS + CMS Run 1 results. The observed (expected) significance for the VBF process is 6.5σ (5.3σ), giving the first single-experiment observation of the VBF production mode. All results are compatible with the SM predictions.

Keywords: LHC, ATLAS, Standard Model, Electroweak Symmetry Breaking, Higgs boson

摘要

2012 年, 大型强子对撞机 (LHC) 上的 ATLAS 和 CMS 实验组宣布利用质心能量在 7 TeV 和 8 TeV 的对撞数据, 发现了质量约为 125 GeV 的希格斯玻色子 (Higgs Boson)。这是粒子物理标准模型中最后被发现的关键粒子, 希格斯玻色子通过对称性自发破缺机制解释基本粒子质量的来源。希格斯玻色子的发现被美国科学杂志评为 2012 年度最重大的科学发现, 同时为 2013 年度的诺贝尔物理学奖提供了最关键的实验证据。

在希格斯粒子发现之后, 希格斯粒子的精确测量成为 LHC 实验上最重要的物理目标之一。双光子衰变道是大型强子对撞机上信号显著度最好的希格斯粒子“黄金衰变道”之一。希格斯粒子衰变到双光子的分支比非常小, 但随着 LHC Run 2 大统计量实验数据的积累, 使得实验上直接测量希格斯玻色子的各种不同产生机制 (例如 ggF, VBF, VH 和 ttH) 成为可能, 这对于精确测量希格斯玻色子的截面和耦合参数具有重要意义。

本文介绍了粒子物理标准模型, 希格斯机制以及寻找和测量希格斯粒子性质的意义, 概述 LHC 加速器和 ATLAS 探测器的基本情况以及探测器上粒子重建、鉴别和刻度的一般方法, 并对 LHC 上测量希格斯粒子性质的工具: 简化模板截面 (Simplified Template Cross Section, STXS) 和希格斯耦合参数模型框架 (κ -framework) 进行了介绍。本文采用 2015-2016 年 ATLAS 探测器积累的质心系能量为 13 TeV 的 36.1 fb^{-1} 实验数据进行分析。在双光子末态的各种产生机制中, 根据信号的特征把重建事例进行优化和分成 31 个信号类别, 提高信号探测灵敏度。然后综合不同希格斯产生机制的双光子衰变道对希格斯玻色子的产生截面和耦合参数进行精确测量。最终全局统计拟合获得希格斯粒子总体信号强度为 0.99 ± 0.14 。

为了进一步提高希格斯粒子各种性质的测量精度, 本文综合了希格斯粒子各种衰变道的实验测量结果, 包括 $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $VH(H \rightarrow bb)$, $H \rightarrow \tau\tau$, $ttH(H \rightarrow \text{Multi-Lepton})$, $ttH(H \rightarrow bb)$, $H \rightarrow \mu\mu$, $VBF(H \rightarrow bb)$, $H \rightarrow \text{invisible}$ 和 $H \rightarrow ZZ(\text{offshell})$ 。积分亮度在 $24.5\text{-}79.8 \text{ fb}^{-1}$ 之间。在不同测量道中通用的实验或者理论误差在综合测量中被关联起来。利用构建的综合统计测量模型, 对于希格斯粒子的产生截面, STXS 截面, κ 模型的相关耦合参数进行全面测量。耦合参数的测量精度比 Run 1 的实验测量精度提高 20%-30%。

综合多个衰变道后，测量获得希格斯粒子的总体信号强度为 $\mu = 1.11^{+0.09}_{-0.08}$ ，得到的 VBF 产生机制信号显著度达到 6.5σ ，这是首次在单一实验上观测到 VBF 产生机制。实验测量结果与标准模型预期值吻合。

关键字: 大型强子对撞机, ATLAS 实验, 粒子物理标准模型, 电弱对称性破缺, 希格斯玻色子

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Introduction

Throughout the history of our civilization, human beings have never ceased to seek the most fundamental constituents of matters in the living world. At different times in history, people have introduced various theories explaining the essential “elements” which act as the elementary building blocks of the universe. The attempt to get the answer is still ongoing today.

“Classical elements” is the common concept to be found in several ancient cultures coincidentally. Starting from the pre-Qin Dynasty period of China, people believed that the whole world, as well as energies and transitions, can be described with the five fundamental elements: Wood, Fire, Earth, Metal, and Water. Ancient Indians classified the material world into Wind, Earth, Fire and Water, and further suggested that all creation, including the human body, consist of these basic elements. The same theory can be found in works of Greek philosopher Empedocles.

“Atomism” turned out to be the most proactive hypothesis in that early age. In the 5th century BC, Leucippus and his pupil Democritus proposed that all matters are composed of small indivisible particles called atoms, which is similar to the theory proposed by the Chinese philosopher Mozi at almost the same time.

After the stagnation in the long and dark Middle Ages in Europe, natural sciences came into the new era during the periods of Renaissance and Enlightenment that followed, as did the understanding of the nature of the matters. Gassendi brought atomism back to the mainstream vision. After that, 19th century should be marked as the true beginning of the atomic physics. The English meteorologist and chemist John Dalton formulated the first scientific theory of the atom. Dalton suggests that each chemical element is composed of a single, unique type of atoms, although they cannot be chemically altered or destroyed, but they can be combined together to form a more complex structure.

The atomic physics then entered a vigorous period of development as a matter of course. However, from the end of the 19th century to the beginning of the 20th century, with the gradual understanding of atomic structures and the discovery of natural radioactivity, there was growing evidence that atoms are not the most basic unit of the matters. J.J. Thomson discovered the electron when he found that

electrically charged plates and magnets deflected a cathode ray in a certain way. Ernest Rutherford determined that the center of the atom is a nucleus, which is surrounded by orbiting electrons, by performing the famous Gold Foil Experiment. James Chadwick then discovered the neutron. This finally confirmed that nuclei are composed of protons and neutrons. With the development of quantum physics and the efforts made by physicists such as Niels Bohr and Wolfgang Pauli, human beings finally got a clearer picture of the structure of atoms.

A large amount of subatomic particles were discovered in the following decades, with the help from various detection methods, including the cosmic-ray study and ever more powerful particle accelerators. For instance, Seth Neddermeyer with Carl Anderson discovered the muon, a negatively charged subatomic particle, in 1936. The pion and kaon mesons were discovered in the 1940s indicating the existence of quarks. In 1956, the team of Frederick Reines and Clyde Cowan discovered the electron neutrino, a subatomic particle with no electric charge. The muon neutrino was discovered as well after 6 years. In 1974, two research groups, one at Stanford Linear Accelerator Center led by Burton Richter and another at Brookhaven National Laboratory led by Samuel Ting discovered J/ψ , a flavor-neutral meson composed of two charm quarks. The tau lepton was discovered in 1975 by Martin Perl. Two years later, upsilon meson was discovered by Fermilab, led by Leon Lederman, confirming the existence of b quarks. The heaviest fermion top quark was then discovered by Fermilab in 1995. While most of the discoveries of fermions were made in the US, bosons were usually probed in Europe. In 1979, the gluon was observed in DESY for the first time. Carlo Rubbia and the CERN UA1 discovered W and Z bosons in 1983.

Meanwhile, theoretical development was also under progress to predict and explain the experimental observations. In 1961, the electromagnetic and weak interactions were combined by Sheldon Glashow. Then in 1967, with the Higgs mechanism integrated by Steven Weinberg and Abdus Salam, Glashow's electroweak interaction got its modern form. It is believed that the Higgs mechanism gives the mass of all elementary particles in the Standard Model, including the masses of the W/Z bosons and the fermions. After the discovery of neutral weak currents produced by Z boson exchange at CERN in 1973, the electroweak theory has been widely accepted. In the strong force part, the theory of the strong interaction known as quantum chromodynamics, QCD, to which many contributed, acquired its modern form in 1973 to 1974. The asymptotic freedom was confirmed by experiments, that hadrons consist of fractionally charged quarks. In 1975, with reference to the electroweak theory together with the quark theory, the term "Standard Model" was first coined by Abraham Pais and Sam Treiman.

The elucidation of the mechanism of electroweak symmetry breaking has been

one of the main goals of the ATLAS and CMS experiments at the CERN LHC, a magnificent international cooperation project started up on 10 September 2008. In the Standard Model, a complex doublet scalar field leads to the breaking of the symmetry and the prediction of the existence of one physical neutral scalar particle, commonly known as the Higgs boson. The Higgs scalar field can also account for fermion masses through Yukawa interactions. If the Higgs boson mass is known, the production cross sections and decay branching fractions of the Higgs boson can be precisely calculated. While its mass is not predicted by the SM.

In July 2012, the ATLAS and CMS collaborations announced the discovery of a Higgs boson with a mass of approximately 125 GeV using proton–proton collisions collected at center-of-mass energies $\sqrt{s} = 7$ TeV and 8 TeV at the LHC. Following the discovery, a broad range of measurements of the boson’s properties have been performed using proton–proton collision data produced by the LHC. The coupling properties of the Higgs boson to other Standard Model (SM) particles, such as its production cross sections in pp collisions and decay branching ratios, can be precisely probed within the SM. Measurements of these properties can therefore provide stringent tests of the validity of the SM.

Two topics in the Higgs sector are covered by this dissertation, including the measurements of the Higgs boson properties in the diphoton decay channel, and the measurement of the Higgs boson production and decay rates, as well as constraints on its couplings to SM particles by combining all available Higgs production modes and decay channels measured by ATLAS. Both of them are based on the proton–proton collision data produced by the LHC at center-of-mass energies of $\sqrt{s} = 13$ TeV and recorded by the ATLAS detector.

Thanks to the high photon reconstruction and identification efficiency at the ATLAS experiment, a reasonably large signal yield can be obtained in spite of the small branching ratio for $H \rightarrow \gamma\gamma$. Furthermore, the excellent photon energy resolution of the ATLAS calorimeter makes the signal appears as a narrow peak in the diphoton invariant mass spectrum. By using an appropriate fit to the $m_{\gamma\gamma}$ distribution of the selected events, the Higgs boson signal yield can be measured.

The combination of Higgs boson decay channels maximizes the precision of these measurements and allows a measurement of the ratio of partial decay widths that is independent of the total width of the Higgs boson. These results increase the experimental sensitivity to new processes at high energy scales that involve the Higgs boson.

The contents of this dissertation are organized as follows. Chapter 1 introduces the Standard Model and Higgs mechanism. Chapter 2 introduces the LHC and the ATLAS experiment. Chapter 3 presents the simulation and the reconstruction of physics object. Chapter 4 discusses the measurements of the Higgs

boson properties in the diphoton decay channel. Chapter 5 talks about the measurement of the Higgs boson production and decay rates as well as constraints on its couplings to SM particles, combining decay channels $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, and $H \rightarrow \gamma\gamma$; and to fermions, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$, and $H \rightarrow \mu\mu$. Finally, the summary and outlook are given in Conclusion.

CHAPTER 1

The Standard Model and Higgs Mechanism

1.1 The Standard Model of particle physics

The Standard Model (SM) is our current understanding of particle physics. It describes elementary particles and the interactions between them, with the exception of gravity. It is a non-Abelian Lorentz invariant and gauge invariant quantum field theory developed starting from the 1960s. Over the past several decades, it has successfully explained most relevant experimental observations with a high degree of precision.

The Standard Model is based on the symmetry group $SU(3) \times SU(2) \times U(1)$, in which the color group $SU(3)$ describes the strong interaction, and $SU(2) \times U(1)$ represents the electroweak (EW) interactions. The Lagrangian can be written as

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} , \quad (1.1)$$

where $\mathcal{L}_{EW}$ and $\mathcal{L}_{QCD}$ represents the Lagrangian of electroweak interaction and the quantum chromodynamics (QCD) term, respectively. These will be discussed in the following part of this chapter.

1.1.1 Elementary particles in the Standard Model

According to the SM, all known matter is comprised of fermions of spin $\frac{1}{2}$. Fermions are elementary particles including quarks (u, d, c, s, t, b) and leptons (e, μ, τ and corresponding neutrinos). The interactions are mediated by spin 1 particles, including strong (by gluons) and electroweak (by photon γ and weak bosons $W^\pm$ and Z). There is a spin 0 scalar Higgs boson that breaks the gauge symmetry to generate masses of the weak force carriers. All the SM elementary particles are summarized in Figure 1.1

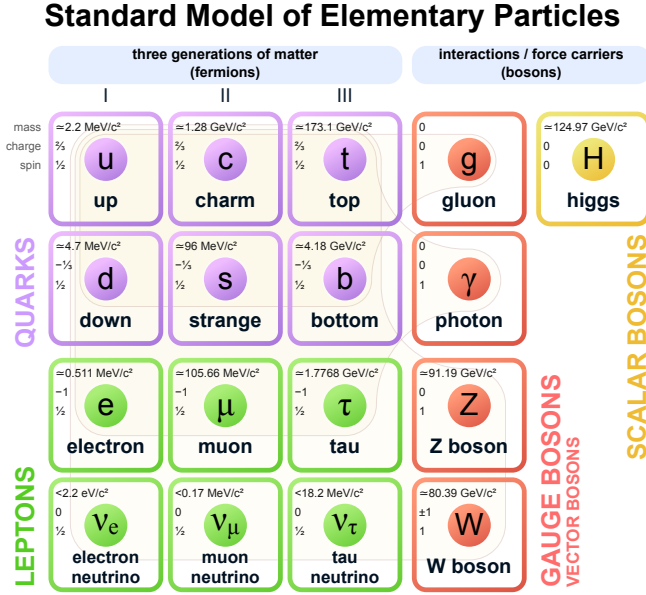


Fig. 1.1: Standard Model of Elementary Particles. Source: Particle Data Group.

Fermions respect the Pauli exclusion principle per the spin–statistics theorem. The fermions of the Standard Model are classified according to how they interact and each fermion has a corresponding antiparticle. The six leptons including e , μ and τ carrying electric charge of -1, and electrically neutral corresponding neutrinos can participate in electroweak interactions. The u, c, t quarks carry electric charge of $2/3$ in unit of e , while d, s, b have $-1/3$. Quarks also carry color charge which allows them to interact via the strong interactions.

In the Standard Model, gauge bosons with a spin of 1 act as force carriers that mediate the strong, weak, and electromagnetic interactions. There are 8 massless gluons as the strong force carriers also carrying color charges. A massless photon acts as the electromagnetic force mediator between electrically charged particles. There are also the Z and the $W^\pm$ bosons which are massive (91.2 GeV and 80.4 GeV, respectively) and mediate the weak interactions, for both quarks and leptons. Electromagnetic and weak interactions are unified as the electroweak interaction in the Standard Model.

The last particle of the Standard Model was discovered in 2012. The Higgs boson with mass around 125 GeV [4] and spin 0 can explain why the other elementary particles, except the photon and gluon, are massive through the Brout-Englert-Higgs mechanism.

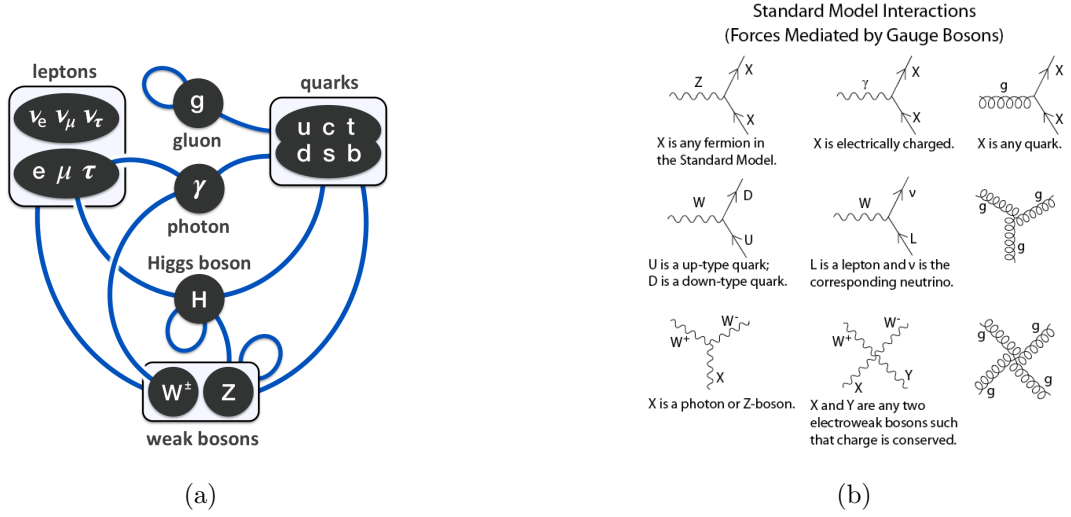


Fig. 1.2: (a) Summary of Standard Model interactions between particles. Source: Wikipedia, Author: Eric Drexler. (b) Vertices in the Standard Model (Except the modifications involving Higgs boson interactions and neutrino oscillations). Source: Wikipedia, Author: Garyzx.

Figure 1.2 summarizes the interactions between particles, and also depicts the corresponding forces mediated by gauge bosons in the SM.

1.1.2 Electroweak interactions and the Brout-Englert-Higgs mechanism

1.1.2.1 The electroweak Lagrangian

The electroweak theory is a unified description of the electromagnetism and weak interactions. The Lagrangian $\mathcal{L}_{EW}$ in Equation 1.1 can be further divided into

$$\mathcal{L}_{EW} = \mathcal{L}_{gauge} + \mathcal{L}_\phi + \mathcal{L}_{fermion} + \mathcal{L}_{Yukawa} , \quad (1.2)$$

where $\mathcal{L}_{gauge}$ is the gauge boson self interaction term, $\mathcal{L}_\phi$ denotes the scalar Higgs field term, $\mathcal{L}_{fermion}$ represents the fermion interaction term and $\mathcal{L}_{Yukawa}$ gives the Yukawa term.

The gauge boson self interaction term is constructed from the field strengths, which can be expressed as

$$\mathcal{L}_{gauge} = -\frac{1}{4}W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} , \quad (1.3)$$

where the $U(1)$ field strength B_μ , and the $SU(2)$ field strengths $W_\mu^i (i = 1, 2, 3)$ are defined from the commutation of two covariant derivatives,

$$\begin{aligned}
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\
W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk}W_\mu^jW_\nu^k,
\end{aligned}
\tag{1.4}$$

Here g is the coupling strength to the $SU(2)$ gauge field and ϵ_{ijk} is the totally anti-symmetric tensor. The Lagrangian in Equation 1.3 is not only quadratic in the derivatives of the gauge boson fields but contains as well three- and four-point self-interaction terms. These give rise to the triple and quartic gauge boson couplings.

The scalar sector fields are described by the Lagrangian invariant under $SU(2) \times U(1)$ transformations. The Lagrangian can be written as

$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger D_\mu \phi - V(\phi), \tag{1.5}$$

where the $SU(2)$ doublet $\phi = (\phi^+, \phi^0)^T$ represents the two complex Higgs fields. The gauge covariant derivative is defined as

$$D_\mu \phi = (\partial_\mu + ig\frac{\tau^i}{2}W_\mu^i + \frac{ig'}{2}B_\mu)\phi, \tag{1.6}$$

where the τ^i are the Pauli matrices, g and g' represent the $SU(2)$ and $U(1)$ coupling constants, respectively. The Higgs self interaction

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2, \tag{1.7}$$

described by the most general fourth-order polynomial. Value of μ such that $\mu^2 > 0$ lead to spontaneous symmetry breaking. $\lambda > 0$ is required for Vacuum stability

The fermion term is invariant under global $SU(2) \times U(1)$ transformations in flavor space, which can be written as:

$$\mathcal{L}_{fermion} = \sum_j \bar{\phi}_L^j i\gamma^\mu D_\mu^L \phi_L^j + \sum_{j,\sigma} \bar{\phi}_{R,\sigma}^j i\gamma^\mu D_\mu^L \phi_{R,\sigma}^j, \tag{1.8}$$

in which $\sigma = \pm$ denotes the up and down type of fermions, L and R denote the

left and right chirality components of the fermion field.

$$\begin{aligned}
\phi_L &= \frac{1}{2}(1 - \gamma_5)\phi, \\
\phi_R &= \frac{1}{2}(1 + \gamma_5)\phi, \\
D_\mu^{L,R} &= \partial_\mu - igI_a^{L,R}W_\mu^a + ig'\frac{Y}{2}B_\mu, \\
I_a^L &= \frac{1}{2}\sigma_a, \\
I_a^R &= 0, \\
a &= 1, 2, 3,
\end{aligned} \tag{1.9}$$

where γ_5 is the fifth gamma matrix.

With the previously introduced scalar field, the gauge invariant Yukawa interaction between the Higgs and fermion fields can be written as:

$$\mathcal{L}_{Yukawa} = - \sum_{m,n=1}^F [\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\phi} u_{nR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \tilde{\phi} d_{nR}^0 + \Gamma_{mn}^e \bar{l}_{mn}^0 \phi e_{nR}^0] + h.c. , \tag{1.10}$$

where Γ matrices are used to described the Yukawa couplings between the single Higgs doublet (ϕ) and different flavors of quarks and leptons (m and n).

1.1.2.2 The Brout-Englert-Higgs mechanism

The symmetry requirements in gauge theory do not allow mass terms in the Lagrangian $\mathcal{L}_{gauge}$, predicting that both the electromagnetism's gauge boson (the photon) and the weak force's gauge bosons (W and Z boson) should have zero mass. While experimental observations confirm that the weak gauge bosons do have masses. Thus a mechanism which leads to the spontaneous symmetry breaking, known as the Brout-Englert-Higgs mechanism [5, 6] is introduced. The corresponding Higgs field generates the masses of the W and Z gauge bosons through the Higgs mechanism. It indicates that the vacuum state does not respect the gauge symmetry, in which a manifestation of potential energy transferred to fundamental particles when they interact with the Higgs field to obtain mass in the form of energy.

The single complex Higgs ϕ doublet in the $SU(2)$ space can be written in a Hermitian basis as

$$\phi = \begin{bmatrix} \phi^\dagger \\ \phi^0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_1 - i\phi_2 \\ \phi_3 - i\phi_4 \end{bmatrix}, \tag{1.11}$$

where $\phi_i = \phi_i^\dagger$ stands for four Hermitian fields. The Higgs self interaction shown in Equation 1.7 can be written as following in this basis:

$$V(\phi) = -\frac{1}{2}\mu^2\left(\sum_{i=1}^4 \phi_i^2\right) + \frac{1}{4}\lambda\left(\sum_{i=1}^4 \phi_i^2\right)^2, \quad (1.12)$$

where an infinite set of degenerate Higgs ground state configuration exist, satisfying $\langle 0|\phi_i|0 \rangle = \sqrt{(\mu^2/\lambda)}$. Without loss of generality, in the four-dimensional space, we can choose $\langle 0|\phi_i|0 \rangle = 0, i = 1, 2, 4$ and $\langle 0|\phi_3|0 \rangle = v$. Equation 1.12 can then be expressed as

$$V(\phi) \rightarrow V(v) = -\frac{1}{2}\mu^2 v^2 + \frac{1}{4}\lambda v^4, \quad (1.13)$$

The sign dependence of μ^2 is shown in Figure 1.3. $SU(2) \times U(1)$ is unbroken at the minimum when $\mu^2 \leq 0$. A spontaneous symmetry breaking can be reached when $\mu^2 > 0$, giving the minimum $v = \sqrt{\mu^2/\lambda}$.

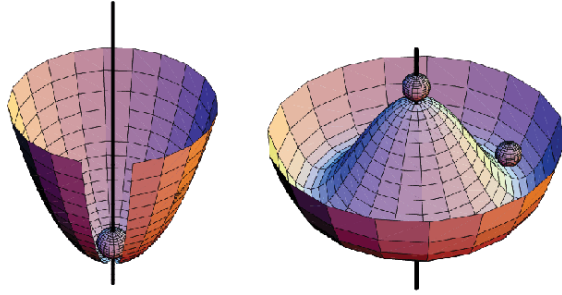


Fig. 1.3: The potential $V(\phi)$ with $\mu^2 \leq 0$ (left) and $\mu^2 > 0$ (right). Author: Jean Iliopoulos.

The scalar sector Lagrangian in Equation 1.5 can be expanded around the classical ground state as its radial degree of freedom times and exponential containing the generators of the broken gauge symmetry

$$\phi = \frac{1}{\sqrt{2}} e^{i\frac{\tau_i}{2}\theta^i(x)} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix}, \quad (1.14)$$

where $h(x)$ is a Hermitian field which will turn out to be the physical Higgs scalar. $\theta^i(x)$ describe the massless particles arising when a spontaneous symmetry breaking happens, the so-called Goldstone bosons. In the unitary gauge, $\theta^i(x) = 0$, the Higgs field becomes

$$\phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix}, \quad (1.15)$$

and the scalar Lagrangian can be written as

$$\begin{aligned}\mathcal{L}_\phi &= (D^\mu \phi)^\dagger D_\mu \phi - V(\phi) \\ &= m_W^2 W^{\mu+} W_\mu^- (1 + \frac{h(x)}{v})^2 + \frac{1}{2} m_Z^2 Z^\mu Z_\mu (1 + \frac{h(x)}{v})^2 + \frac{1}{2} (\partial_\mu h(x))^2 - V(\phi) ,\end{aligned}\tag{1.16}$$

by introducing the weak mixing angle θ_W with $\tan \theta_W = \frac{g'}{g}$, the gauge boson masses are

$$\begin{aligned}m_W &= g \frac{v}{2}, \\ m_Z &= \sqrt{g^2 + g'^2} \frac{v}{2} = \frac{m_W}{\cos \theta_W},\end{aligned}\tag{1.17}$$

The gauge fields can be expressed as

$$\begin{aligned}W^\pm &= \frac{1}{\sqrt{2}} (W^1 \mp i W^2), \\ Z &= -\sin \theta_W B + \cos \theta_W W^3,\end{aligned}\tag{1.18}$$

The Higgs potential in the unitary gauge can be then written as

$$V(\phi) = \frac{\mu^4}{4\lambda} + \mu^2 h(x)^2 + \lambda v h(x)^3 + \frac{\lambda}{4} h(x)^4 ,\tag{1.19}$$

In $V(\phi)$, the third and fourth terms denote the cubic and quartic interactions of the Higgs scalar. The Higgs mass is expressed in the second term of Equation 1.19 by

$$m_h = \sqrt{2\mu^2} = \sqrt{2\lambda} v ,\tag{1.20}$$

Fermion masses are generated by the Yukawa coupling term in Equation 1.2 when the Higgs field acquires a Vacuum Expectation Value (VEV) and breaks $SU(2)$ spontaneously. The Yukawa term in Equation 1.10 can be simply written as :

$$\mathcal{L}_{Yukawa} = - \sum_F m_F \bar{\phi}_F \phi_F - \sum_F \frac{m_F}{v} \bar{\phi}_F \phi_f h(x) ,\tag{1.21}$$

from which the masses m_f for the fermions can be read off:

$$m_F = F_i \frac{v}{\sqrt{2}}, i = e, u, d ,\tag{1.22}$$

where F_i stands for the Yukawa coupling which is proportional to the mass of fermions.

1.2 The Higgs processes at the LHC

1.2.1 Higgs boson production at Large Hadron Collider

The Higgs boson production in proton-proton collisions at the LHC is mainly via the following production modes:

- gluon-gluon fusion (ggF) through a heavy quark loop, $gg \rightarrow H$;
- vector boson fusion (VBF), characterized by the presence of two highly energetic jets with a large $\Delta\eta$ gap, $qq' \rightarrow qq'H$;
- associated production with a W boson (WH) or a Z boson (ZH), $q\bar{q} \rightarrow WH/ZH$ (Higgs-strahlung), including a small contribution (around 8%) from $gg \rightarrow ZH$ ($ggZH$);
- production in association with heavy top or bottom quark pair, $t\bar{t}H$ and $b\bar{b}H$, $q\bar{q}/gg \rightarrow t\bar{t}H, b\bar{b}H$;
- associated production with a single top quark (tH), including t-channel (tHq) $qg \rightarrow tHq'b$ processes and association with a W boson (tHW) $gb \rightarrow tHW$.

Compared to the single Higgs production mechanisms, the pair production mode is suppressed by power of the additional EW vertices which reduces its contribution. Figure 1.4 shows the predicted Higgs production cross section at $\sqrt{s} = 13$ TeV as a function of Higgs boson mass between 120 GeV and 130 GeV.

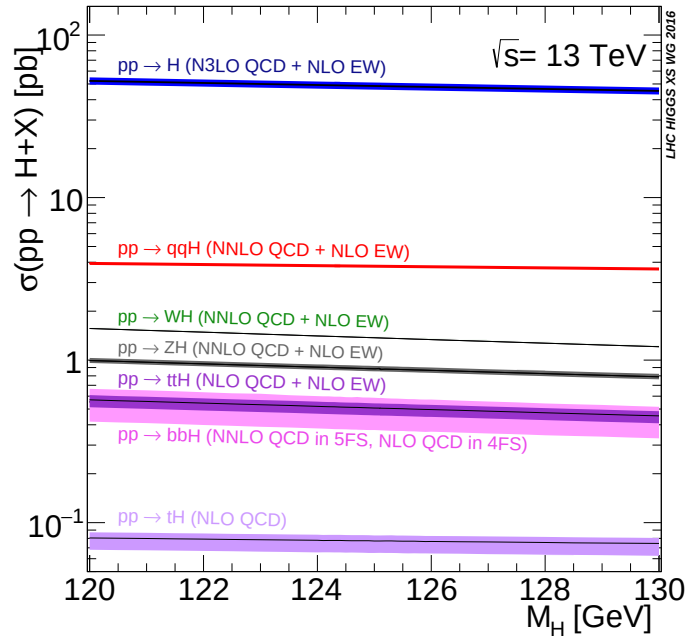


Fig. 1.4: Standard Model Higgs boson production cross sections at $\sqrt{s} = 13$ TeV as a function of Higgs boson mass. Source: LHC Higgs XS WG.

The ggF production process involves a loop process at lowest order, with contributions from t - and b -quark loops and a small interference between them. It is the dominant production process at the LHC, contributing to around 90% of the total production cross sections at $m_h = 125$ GeV. It is the leading production mode to study the Higgs properties. The leading-order Feynman diagram of ggF is shown in Figure 1.5a.

The VBF production process accounts for around 7% of the total Higgs production cross-section, which is the second largest. The two forward jets in the topology can be used to distinguish it from the ggF production mode. VBF probes a combination of vector boson couplings, with a negligible amount (0.1 %) of interference between these tree-level contributions. The Feynman diagram can be found in Figure 1.5b.

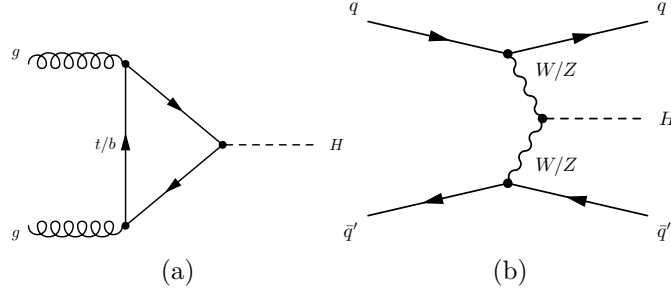


Fig. 1.5: Feynman diagrams of Higgs boson production via (a) ggF and (b) VBF production modes.

VH production modes takes around 4% of the total Higgs production cross section at $\sqrt{s} = 13$ TeV. The $qq \rightarrow WH$ and $qq \rightarrow ZH$ processes (Figure 1.6a) probe couplings to W boson and Z boson, respectively. Their unique event topology can be splitted from the major production modes like ggF and VBF. The gluon-initiated associated production of a Higgs boson with a Z boson, $ggZH$, is characterised by gluon-fusion-style production involving t , b -quark loops where the Higgs boson is either radiated directly from the fermion loop (Figure 1.6b), or is radiated from the outgoing Z boson (Figure 1.6c).

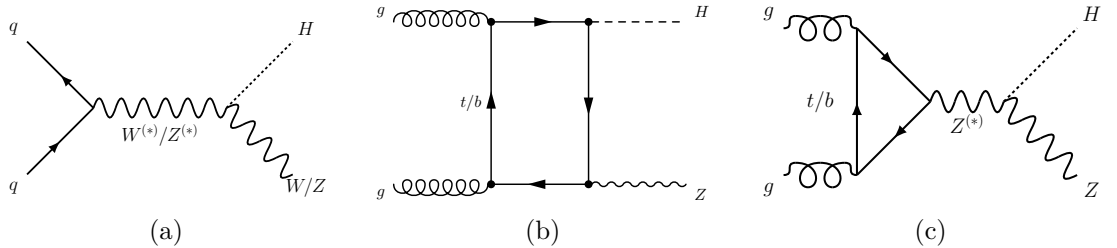


Fig. 1.6: Feynman diagrams of Higgs boson production via (a) $q\bar{q} \rightarrow WH/ZH$ and (b, c) $gg \rightarrow ZH$ production modes.

The $t\bar{t}H$ production process (Figure 1.7a) directly probes the Higgs boson coupling strength to top quarks. It is crucial to probe the Yukawa coupling as the top is the heaviest fermion. The $b\bar{b}H$ process has a smaller cross section, and more difficult to study due to the low tagging efficiency of the much softer b -quark. The tree-level tH production, comprising the processes tHq (Figure 1.7b, 1.7c) and tHW (Figure 1.7d, 1.7e), has a large destructive interference between contributions where the Higgs boson is radiated from the W boson and from the top quark. Therefore, it can be used to constrain the sign of Yukawa couplings between the Higgs boson and the top quark. The SM cross section predicted for tH production is relatively small, about 18% of the $t\bar{t}H$ cross section.

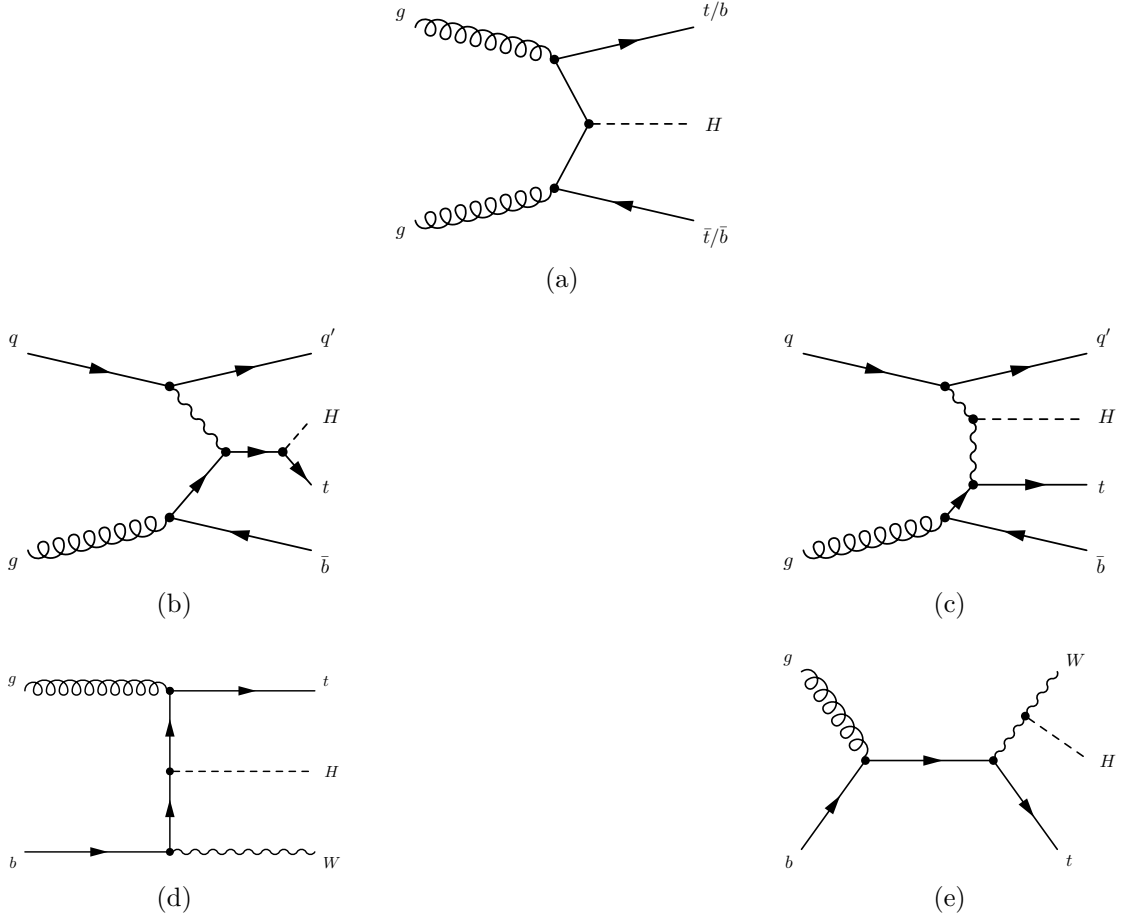


Fig. 1.7: Feynman diagrams of Higgs boson production via (a) $t\bar{t}H$ ($b\bar{b}H$), (b, c) tHq and (d, e) tHW production modes.

1.2.2 Higgs boson decay branching ratio and total width

The total width of the SM Higgs boson with m_h at 125 GeV is predicted to be around 4 MeV. Once the Higgs boson mass fixed, the decay branching ratios of Higgs boson to massive particles can be calculated, as the partial width depends on the square of of the Higgs couplings to the decay products, which are proportional

to their masses. The heavier the particle is, the larger the partial decay width is allowed by phase space. Figure 1.8 shows the Feynman diagrams of Higgs boson decaying into particle with mass.

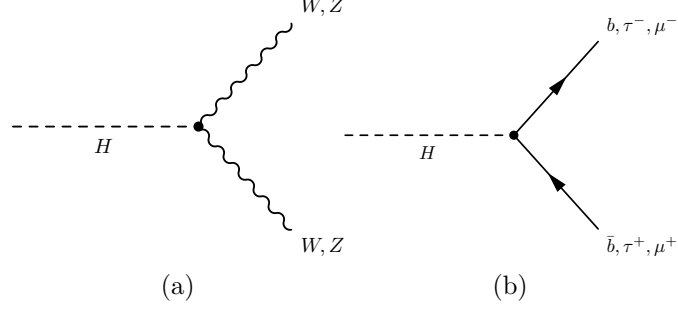


Fig. 1.8: Feynman diagrams of Higgs boson decays (a) to gauge bosons and (b) to fermions.

For massless particles such as photons and gluons, their contributions to the Higgs total width are via loop induced processes. The destructive interference between the W boson and the top quark in the loop can be used to check the sign degeneracy between Higgs boson couplings to bosons versus to fermions and to probe the potential new physics.

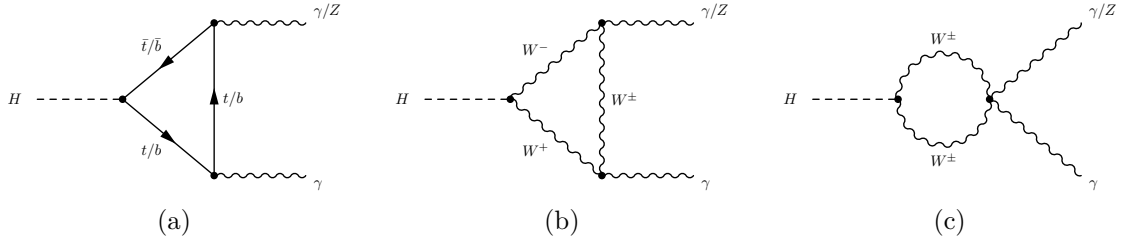


Fig. 1.9: Feynman diagrams of Higgs boson decays via $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ modes.

The SM Higgs boson branching ratios at $m_h = 125.09$ GeV are listed in Table 1.1. The dominant decay mode is $H \rightarrow b\bar{b}$ (57.5%). The $H \rightarrow \gamma\gamma$ branching ratio is around 0.227%.

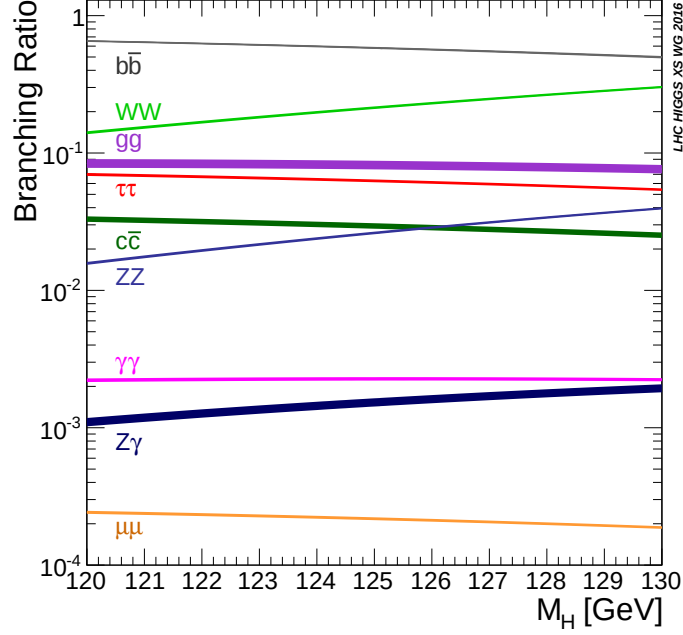


Fig. 1.10: Standard Model Higgs boson decay branching ratios. Source: LHC Higgs XS WG.

Decay mode	Branching ratio [%]
$H \rightarrow b\bar{b}$	57.5 ± 1.9
$H \rightarrow WW^*$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow c\bar{c}$	2.90 ± 0.35
$H \rightarrow ZZ^*$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.227 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001

Table. 1.1: Decay branching fractions of a Higgs boson with a mass of 125.09 GeV predicted by the Standard Model, together with their theoretical uncertainties. Source: LHC Higgs XS WG.

1.3 Simplified template cross sections

Simplified template cross sections [3, 7] are defined through a partition of the phase space of the SM Higgs production process into a set of non-overlapping regions. These regions are defined in terms of the kinematics of the Higgs boson and, when they are present, of associated jets and W/Z bosons, independently of the Higgs boson decay process. They are chosen according to three criteria: sensitivity to deviations from the SM expectation, avoidance of large theory uncertainties in the corresponding SM predictions, and to approximately match experimental selections so as to minimize model-dependent extrapolations. Analysis selections

do not however necessarily correspond exactly to the Simplified template cross sections (STXS) regions.

All regions are defined for a Higgs boson rapidity y_H satisfying $|y_H| < 2.5$, corresponding approximately to the region of experimental sensitivity. Anti- k_t algorithm with a jet radius parameter $R = 0.4$ is used to reconstruct jets from all stable particles with a lifetime greater than 10 ps, excluding the Higgs decay products, and with a transverse momentum $p_{T,\text{jet}} > 30$ GeV.

The measurements presented in Chapter 4 and Chapter 5 are based on the Stage 1 splitting of the STXS framework. Higgs boson production is first classified according to the nature of the initial state and of associated particles, the latter including the decay products of W and Z bosons if they are present. These categories are, by order of decreasing selection priority: $t\bar{t}H$ and tH processes; $qq \rightarrow Hqq$ processes, with contributions from both VBF production and quark-initiated $q\bar{q} \rightarrow WH/ZH$ production with a hadronic decay of the gauge boson; $gg \rightarrow ZH$ with $Z \rightarrow q\bar{q}$; VH production with a leptonic decay of the vector boson ($V(\text{lep})H$), including $gg \rightarrow ZH$ production; and finally the gluon fusion process. The last is considered together with $gg \rightarrow ZH$, $Z \rightarrow q\bar{q}$ production, as a single $gg \rightarrow H$ process. The $b\bar{b}H$ production mode is modeled as a 1% [3] increase of the $gg \rightarrow H$ yield in each STXS bin, since the acceptances for both processes are similar for all input analyses [3]. The $t\bar{t}H$ and tH processes are also combined in a single $t\bar{t}H+tH$ category, assuming the relative fraction of each component to be as in the SM, within uncertainties. The Stage 1 binning for gluon fusion production, vector boson fusion production and associated production with vector bosons are shown in Figure 1.11, 1.12 and 1.13, respectively. Those STXS Stage 1 regions are summarized in Table 1.2. The STXS measurements are discussed in Section 4.9.4 and Section 5.7.

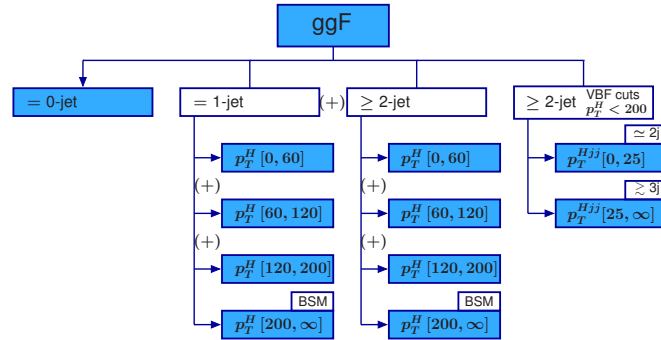


Fig. 1.11: STXS Stage 1 binning for the gluon fusion production.

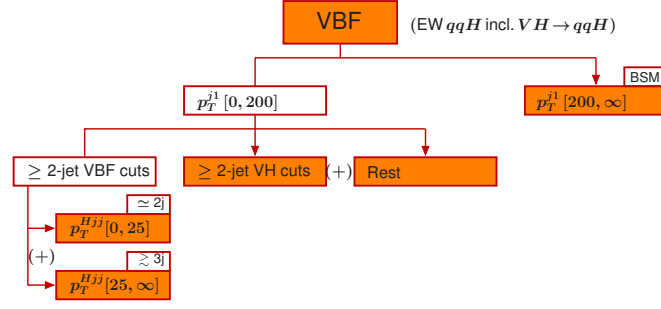


Fig. 1.12: STXS Stage 1 binning for the vector boson fusion production.

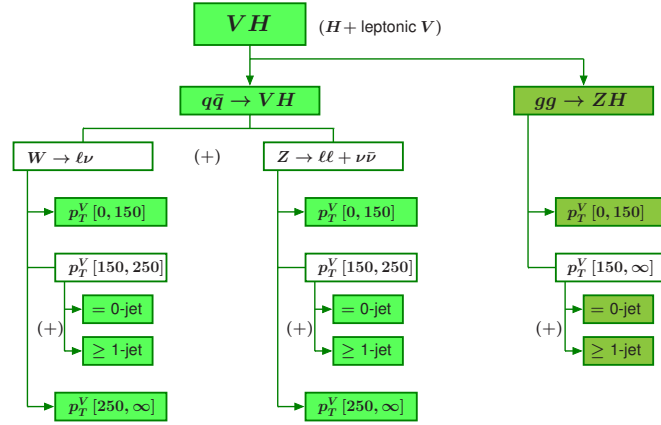


Fig. 1.13: STXS Stage 1 binning for the associated production with vector bosons.

Process	Particle-level stage-1 region
$ggH + gg \rightarrow Z(\rightarrow qq)H$	0-jet 1-jet, $p_T^H < 60$ GeV 1-jet, $60 \leq p_T^H < 120$ GeV 1-jet, $120 \leq p_T^H < 200$ GeV 1-jet, $p_T^H > 200$ GeV ≥ 2 -jet, $p_T^H > 200$ GeV ≥ 2 -jet, $p_T^H < 60$ GeV ≥ 2 -jet, $60 \leq p_T^H < 120$ GeV ≥ 2 -jet, $120 \leq p_T^H < 200$ GeV $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} < 25$ GeV $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} \geq 25$ GeV
$qq' \rightarrow Hqq'$ (VBF + VH)	$p_T^j < 200$ GeV, $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} < 25$ GeV $p_T^j < 200$ GeV, $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} \geq 25$ GeV $p_T^j < 200$ GeV, $q\bar{q} \rightarrow WH/ZH$ -like $p_T^j < 200$ GeV, Rest $p_T^j > 200$ GeV
VH (leptonic decays)	$q\bar{q} \rightarrow ZH$, $p_T^Z < 150$ GeV $q\bar{q} \rightarrow ZH$, $150 < p_T^Z < 250$ GeV, 0-jet $q\bar{q} \rightarrow ZH$, $150 < p_T^Z < 250$ GeV, ≥ 1 -jet $q\bar{q} \rightarrow ZH$, $p_T^Z > 250$ GeV $q\bar{q} \rightarrow WH$, $p_T^W < 150$ GeV $q\bar{q} \rightarrow WH$, $150 < p_T^W < 250$ GeV, 0-jet $q\bar{q} \rightarrow WH$, $150 < p_T^W < 250$ GeV, ≥ 1 -jet $q\bar{q} \rightarrow WH$, $p_T^W > 250$ GeV $gg \rightarrow ZH$, $p_T^Z < 150$ GeV $gg \rightarrow ZH$, $p_T^Z > 150$ GeV, 0-jet $gg \rightarrow ZH$, $p_T^Z > 150$ GeV, ≥ 1 -jet
Top-associated production	$t\bar{t}H$ tHq and tHW
$b\bar{b}H$	$b\bar{b}H$

Table. 1.2: Kinematic regions of the Stage 1 simplified template cross sections.

1.4 Framework for coupling-strength measurements

Coupling strength modifiers κ are introduced to study modifications of the Higgs boson couplings related to BSM physics, within a framework [2] (κ -framework) based on the leading-order contributions to each production and decay process. Within the assumptions made in this framework, the Higgs boson production and decay can be factorized, such that the cross section times branching fraction of an individual channel $\sigma(i \rightarrow H \rightarrow f)$ contributing to a measured signal yield is parametrised as

$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}, \quad (1.23)$$

where Γ_H is the total width of the Higgs boson and Γ_f is the partial width for Higgs boson decay to the final state f . For a given production process or decay

mode j , the corresponding coupling strength modifier κ_j is defined by

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}. \quad (1.24)$$

The SM expectation, denoted by the label SM, by definition corresponds to $\kappa_j = 1$. Modifications of the coupling scale factors also change the Higgs boson total width Γ_H by a factor κ_H , given by $\kappa_H^2 = \sum_j B_f^{\text{SM}} \kappa_j^2$.

The total width of the Higgs boson increases beyond modifications of κ_j due to contributions from two additional classes of Higgs boson decays: invisible decays, which are identified through an E_T^{miss} signature in the analyses described in Section 5.3.8; and undetected BSM decays, to which none of the analyses included in this combination are sensitive (the latter includes for instance Higgs boson decays to light quarks, or to BSM particles to which none of the input analyses provide appreciable sensitivity). In the SM, the branching ratio for decays to invisible final states is $\sim 0.1\%$, from the $H \rightarrow ZZ^* \rightarrow 4\nu$ process. BSM contributions to this branching fraction and to the branching fraction to undetected BSM final states are denoted by B_{inv} and B_{undet} respectively, with the SM corresponding to $B_{\text{inv}} = B_{\text{undet}} = 0$. The Higgs boson total width is then expressed as

$$\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv}}, B_{\text{undet}}) = \frac{\kappa_H^2(\boldsymbol{\kappa})}{(1 - B_{\text{inv}} - B_{\text{undet}})} \Gamma_H^{\text{SM}}. \quad (1.25)$$

Constraints on B_{inv} are provided by the analyses described in Section 5.3.8, but no direct constraints are included for B_{undet} . Since all observed cross sections of on-shell Higgs boson production $\sigma(i \rightarrow H \rightarrow f)$ is scaled by its value through Eqs. 1.23 and 1.25, further assumptions about undetected BSM decays are included to interpret these measurements by using absolute coupling-strength scale factors κ_j . The SM gives the simplest assumption that there are no undetected BSM Higgs boson decays and the invisible branching fraction. An alternative, weaker assumption, is to require $\kappa_W \leq 1$ and $\kappa_Z \leq 1$ [2]. Another alternative assumption is that the signal strength of off-shell Higgs boson production does not depend on the total width, but on the coupling-strength scale factors [8, 9], $\sigma^{\text{off}}(i \rightarrow H^* \rightarrow f) \sim \kappa_{i,\text{off}}^2 \times \kappa_{f,\text{off}}^2$. If there is an assumption that the coupling strengths in off-shell Higgs boson production are identical to those for on-shell Higgs boson production, $\kappa_{j,\text{off}} = \kappa_{j,\text{on}}$, the Higgs boson total width can thereby be determined from the ratio of off-shell to on-shell signal strengths [10, 11]. These assumptions can also be extended to apply to B_{inv} as well as B_{undet} , as an alternative to the measurements of Section 5.3.8.

An alternative approach is to rely on measurements of ratios of coupling strength scale factors, which can be measured without assumptions on the Higgs

boson total width, since the dependence on Γ_H of each coupling strength cancels in their ratios.

The current LHC data are insensitive to the κ_c and κ_s . Thus, the assumptions are introduced that κ_c varies as κ_t and κ_s varies as κ_b . Other coupling modifiers (κ_u , κ_d , and κ_e) are of order unity. The $gg \rightarrow H$, $H \rightarrow gg$, $ggZH$, $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ processes are loop induced in the SM. The ggH vertex and the $H \rightarrow \gamma\gamma$ process are treated either using effective scale factors κ_g and κ_γ , respectively, or expressed in terms of the more fundamental coupling strength scale factors corresponding to the particles that contribute to the loop, including all interference effects. The $ggZH$ process is never described using an effective scale factor and always resolved in terms of modifications of the SM Higgs boson couplings to the top quark and the Z boson. This assumption impacts the description of BSM effects in $ggZH$, since these lead to modified production kinematics [12]. However the effect of introducing an explicit dependence on the transverse momentum of the Z boson in the parameterization was found to have a negligible impact on the results at the current level of experimental precision. Similarly, the $H \rightarrow Z\gamma$ decay is always expressed in terms of the Higgs boson couplings to the W boson and the t quark as no analysis targeting this decay mode is included in the combination. These relations are summarized in Table 1.3. Results of the coupling strength framework are discussed in Section 4.9.5 and Section 5.8.

Production	Loops	Interference	Effective modifier	Resolved modifier
$\sigma(gg \rightarrow H)$	✓	$t - b$	κ_g^2	$1.04 \kappa_t^2 + 0.002 \kappa_b^2 - 0.04 \kappa_t \kappa_b$
$\sigma(qq' \rightarrow qq' H)$	-	-	-	$0.73 \kappa_W^2 + 0.27 \kappa_Z^2$
$\sigma(qqZH)$	-	-	-	κ_Z^2
$\sigma(ggZH)$	✓	$t - Z$	$\kappa_{(ggZH)}$	$2.46 \kappa_Z^2 + 0.46 \kappa_t^2 - 1.90 \kappa_Z \kappa_t$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(q\bar{q}/gg \rightarrow t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	$t - W$	-	$2.91 \kappa_t^2 + 2.31 \kappa_W^2 - 4.22 \kappa_t \kappa_W$
$\sigma(tHq)$	-	$t - W$	-	$2.63 \kappa_t^2 + 3.58 \kappa_W^2 - 5.21 \kappa_t \kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	$t - b$	κ_g^2	$1.11 \kappa_t^2 + 0.01 \kappa_b^2 - 0.12 \kappa_t \kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2 (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	$t - W$	κ_γ^2	$1.59 \kappa_W^2 + 0.07 \kappa_t^2 - 0.67 \kappa_W \kappa_t$
$\Gamma^{Z\gamma}$	✓	$t - W$	$\kappa_{(Z\gamma)}^2$	$1.12 \kappa_W^2 - 0.12 \kappa_W \kappa_t$
Γ^{ss}	-	-	-	$\kappa_s^2 (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{inv}} = B_{\text{undet}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.58 \kappa_b^2 + 0.22 \kappa_W^2$ $+0.08 \kappa_g^2 + 0.06 \kappa_\tau^2$ $+0.03 \kappa_Z^2 + 0.03 \kappa_c^2$ $+0.0023 \kappa_\gamma^2 + 0.0015 \kappa_{(Z\gamma)}^2$ $+0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$

Table. 1.3: Parametrizations of Higgs boson production cross sections σ_i , partial decay widths Γ_f , and the total width Γ_H , normalized to their SM values, as functions of the coupling strength modifiers κ . The effect of invisible and undetected BSM decays is not considered in the expression for Γ_H . For loop-induced effective κ parameters, the resolved scaling in terms of the modifications of the Higgs boson couplings to the fundamental SM particles is given. The coefficients are derived following the methodology in Ref. [2].

CHAPTER 2

The Large Hadron Collider and the ATLAS Experiment

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [13, 14, 15, 16] is the largest particle collider, as well as the largest machine in the world, located at the European Organization for Nuclear Research (CERN), the France–Switzerland border near Geneva. It’s a circular proton-proton collider with a circumference of 27 km and a depth of 50 to 175 m beneath the ground; its designed maximum center-of-mass energy of proton-proton collision is $\sqrt{s} = 14$ TeV, with heavy-ion collisions also included in the program reaching an energy of 2.3 TeV per nucleon. The collider has four crossing points around the accelerator ring, corresponding to the positions of four major particle detectors: ATLAS [17], CMS [18], ALICE [19] and LHCb [20]. ATLAS and CMS are large general-purpose particle detectors, studying the Higgs boson and searching for signs of new physics, including the origin of mass and extra dimensions. ALICE and LHCb have more specific roles. ALICE mainly studies quark–gluon plasma produced by heavy-ion collisions, while LHCb is a specialized B-physics experiment.

2.1.1 Design parameters and machine layout

The LHC is housed in a circular tunnel with a circumference of 26.7 km and a width of 3.8 m. The tunnel was constructed between 1983 and 1988 and was previously used to house the Large Electron–Positron Collider (LEP). The collider has two adjacent parallel beamlines, each with proton beam travelling in opposite directions around the ring. There are four beams intersect points around the ring where the particle collisions take place. Magnets are used to keep the beams on their circular path and focused. In the place close to the intersection points, there are also stronger quadrupole magnets used to maximize the chances of interaction

where the two beams cross.

The LHC is designed to have a nominal instantaneous luminosity of $L = 10^{34} \text{cm}^{-2} \text{s}^{-1}$, which is defined as the number of particles per area per time during collisions. Based on the assumption of a Gaussian beam distribution,

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F, \quad (2.1)$$

in which N_b refers to the number of particles per bunch, n_b the numbers of bunches per beam, γ_r the relativistic gamma factor, f_{rev} the revolution frequency, β^* the beta function at the collision point and ϵ_n the normalized transverse beam emittance. F refers to the geometric luminosity reduction factor due to the crossing angle at the interaction point (IP),

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}, \quad (2.2)$$

Where θ_c is the full crossing angle at the IP, σ^* the transverse Root Mean Square (RMS) of beam size at the IP, σ_z the RMS of bunch length.

Table 2.1 shows the design parameter of LHC to reach a peak luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ for proton-proton collisions at $\sqrt{s} = 14 \text{ TeV}$.

Circumference	26.7 km
Beam energy at collision	7 TeV
Beam energy at injection	0.45 TeV
Beam current	0.56 A
Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$
Number of bunches	2808
Protons per bunch	1.11×10^{11}
Nominal bunch spacing	24.95 ns
Normalized emittance	$3.75 \mu\text{m}$
Critical synchrotron energy	44.1 eV
Radiated power per beam	3.8 kW
Total crossing angle	$300 \mu\text{rad}$
Dipole field at 7 TeV	8.33 T
Stored energy in magnets	11 GJ
Stored energy per beam	350 MJ
Energy loss per turn	6.7 keV
Operating temperature	1.9 K

Table. 2.1: LHC design parameters.

The colliding particles traverse a chain of pre-accelerators, which is shown in Figure 2.1. Protons produced from stripping off the valence electron of Hydrogen atoms are accelerated to 50 MeV in the linear accelerator 2 (LINAC2), the first accelerator in the whole chain. Then they are injected into the Proton Synchrotron Booster (PSB), gaining energy up to 1.4 GeV. The remaining two circular pre-accelerators, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS), will continue to increase the energy of protons to 25 GeV and 450 GeV, respectively.

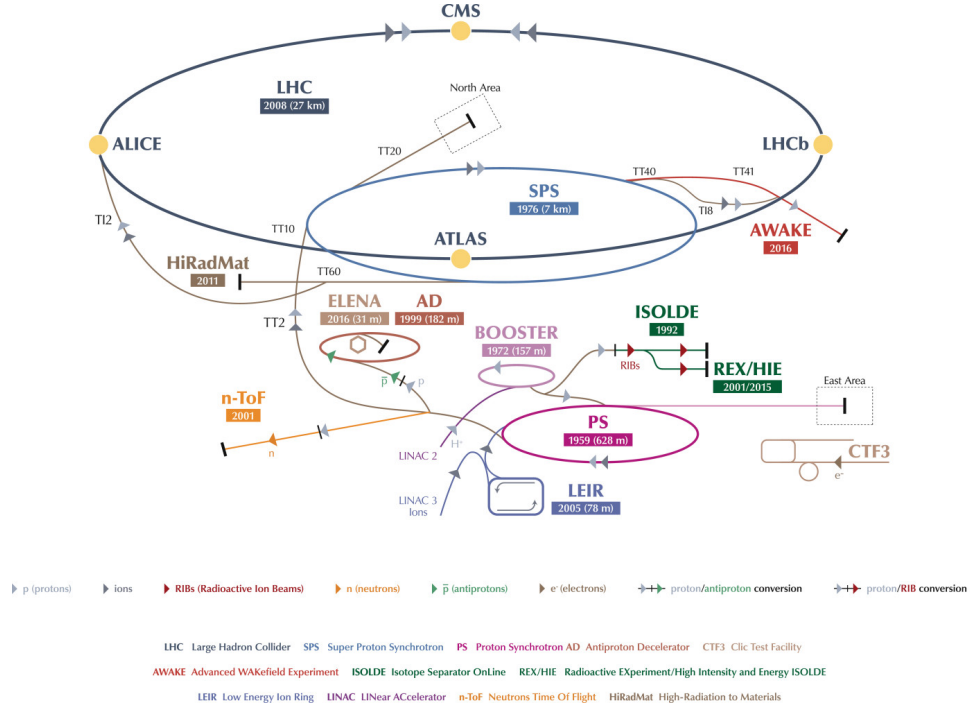


Fig. 2.1: The CERN accelerator complex. Source: LHC complex.

Protons are arranged in bunches of nominally 1.11×10^{11} and injected into the LHC with bunch spacing down to around 25 ns. With continuous acceleration around 20 min, protons will eventually reach the goal energy of 6.5 TeV as currently LHC is operated at $\sqrt{s} = 13$ TeV. Then the collisions take place at the four experiments, which can be found in Figure 2.2 showing the LHC facilities and its underground layout.

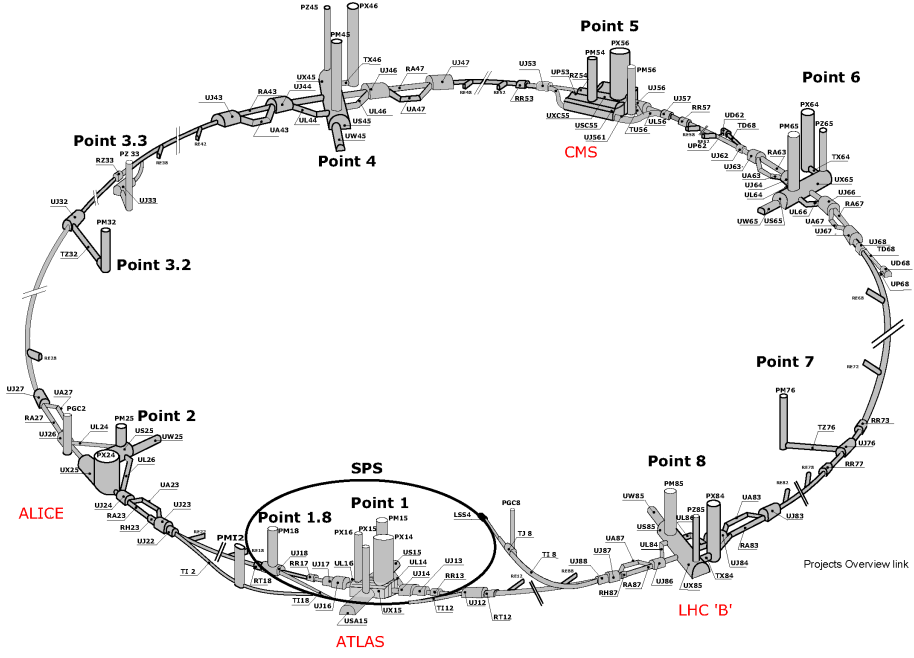


Fig. 2.2: The LHC underground layout. Source: LHC complex.

2.1.2 Operation status

The installation of LHC was between 1998 and 2008, but a 14-month-delay happened for the initial testing due to a magnet quench incident. From March 2010 to February 2013, physics runs took place at $\sqrt{s} = 7$ TeV and 8 TeV, denoted “Run 1”. After the first long shutdown of two years with upgrade including enabling collisions at 14 TeV, enhancing the performance of detectors and pre-accelerators, the LHC restarted to take data at a center-of-mass energy at 13 TeV, which is kept during the second 4-year operation period called “Run 2”. The peak luminosity in 2018 fills reached $21.0 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$, twice the design luminosity mentioned above.

In reality, the instantaneous luminosity (Equation 2.1) changes with time. As a result, the total number of events generated in collision is then given by

$$N_{events} = \mathcal{L} \sigma_{event}, \mathcal{L} = \int L dt, \quad (2.3)$$

in which we get $\mathcal{L}$ the integrated luminosity, in units of inverse barns, where $1 \text{ b} = 10^{-28} \text{m}^2$.

The total delivered integrated luminosity in Run 2 is 156 fb^{-1} . Figure 2.3 shows the status of integrated luminosity versus time for proton-proton collision at LHC.

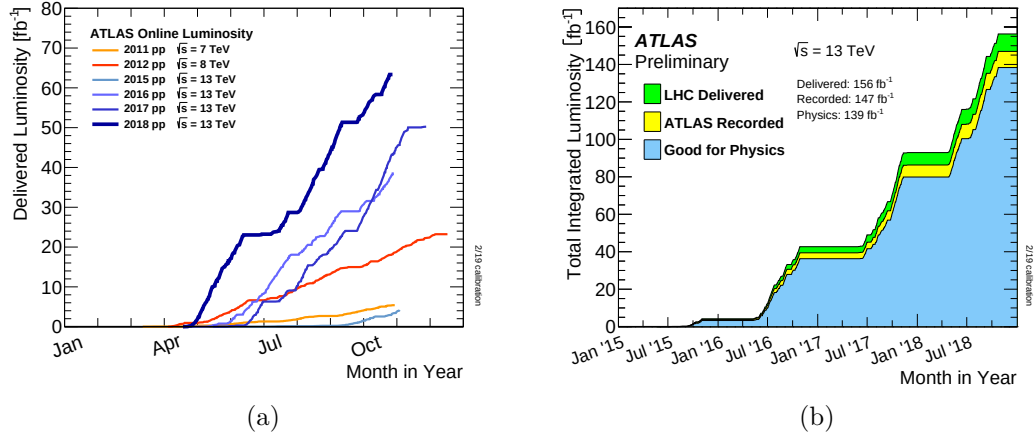


Fig. 2.3: (a) Cumulative luminosity versus time delivered to ATLAS for high energy p-p collisions during stable beams. (b) Cumulative luminosity versus time for collisions delivered to ATLAS (green) and recorded by ATLAS (yellow) for pp collisions at a center-of-mass energy 13 TeV in LHC Run 2 during stable beams.

The number of inelastic proton-proton interactions per bunch crossing called pile-up events, follows a Poisson distribution with mean value μ . The pile-up effect is usually proportional to the beam intensity, inversely proportional to the bunch crossing. μ can be expressed by Equation 2.4

$$\langle \mu \rangle = \frac{L_{bunch} \sigma_{inel}}{f_r n_b}, \quad (2.4)$$

Where L_{bunch} is the instantaneous luminosity for each bunch, σ_{inel} the inelastic cross section, n_{bunch} the number of colliding bunches, and f_{rev} the revolution frequency.

Figure 2.4 shows the standalone and stacked interactions per crossing for the Run 2 pp collision data at 13 TeV center-of-mass energy. The average $\langle \mu \rangle$ value for the entire Run 2 is around 33.7.

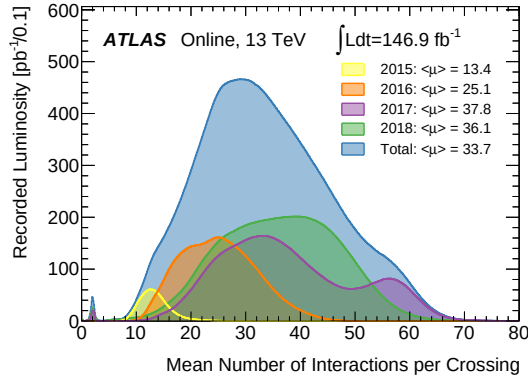


Fig. 2.4: Mean number of interactions per crossing for the Run 2 pp collision data at 13 TeV center-of-mass energy.

2.2 The ATLAS Experiment

The ATLAS (A Toroidal LHC ApparatuS) detector [17], constructed at the Large Hadron Collider (LHC), is a general-purpose particle detector experiments. The aim of this experiment is to use the unprecedented energy of the Large Hadron Collider to observe phenomena involving high-mass particles that were not observed at the early low-energy accelerators. Investigating the Higgs sector in the Standard Model is also a goal for ATLAS, as well as searching for evidences of theories of particle physics beyond the Standard Model.

2.2.1 Detector overview

The ATLAS detector is 46 meters long, 25 meters in diameter and weighs about 7,000 tons. It contains around 3000 km of cables. The ATLAS detector covers almost the entire solid angle around the proton-proton collisions LHC provided by combining several sub-detector systems installed around the interaction point. The coordinate system and nomenclature of the ATLAS detector which are repeatedly used throughout this thesis, are briefly described here. The nominal interaction point (IP) is the origin of the coordinate system, while the the z-axis defined as the beam direction and the x-y plane is transverse to the beam direction. As for the sign of x-y coordinates, starting from the interaction point, the positive x-axis is defined as pointing to the center of the LHC ring and the positive y-axis is defined as pointing upwards. The side-A and side-C of the detector are defined with positive z and negative z, respectively. The azimuthal angle ϕ is defined around the beam axis, and the polar angle θ is the angle measured from the beam axis. For normal objects, the pseudo-rapidity η defined as $-\ln \tan \theta/2$ is used, while the rapidity $y = 1/2 \ln [(E + p_z)/(E - p_z)]$ is used for massive objects. The missing transverse energy E_T^{miss} , the transverse momentum p_T and the transverse energy E_T are defined in the x-y plane. Furthermore, The distance ΔR is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ in the pseudorapidity-azimuthal angle space.

As a part of its initial goal for a general-purpose particle detector, giving a precise measurement of the Standard Model parameters including the Higgs sector requires the good performance from several GeV to hundreds GeV energy scale. On the other hand, searching for the new physics beyond the Standard Model also asks for the excellent detector capacity at the TeV region, to which the characteristic energy scale, proposed by several new models, belongs. In addition, the high inelastic event rate produced on LHC, together with the fact that the QCD jet production cross sections dominate over the rare targeting productions, poses a serious experimental difficulty. As a result, the ATLAS detector is designed to fulfill the following requirements:

- High detector granularity.
- High acceptance with almost full azimuthal angle coverage in pseudorapidity.
- Fast, radiation-hard electronics and sensor elements.
- Capability to observe secondary vertices by the vertex detectors close to the interaction region.
- Good inner tracker performance for charged-particle momentum resolution and reconstruction efficiency.
- Good performance for electron and photon identification and measurements provided by electromagnetic (EM) calorimetry.
- Accurate jet and E_T^{miss} measurements delivered by hadronic calorimeter with full-coverage.
- Good muon identification and momentum resolution with a wide range of muon momenta covered, and also the ability to determine the charge of high p_T muons.
- High efficient triggering on low p_T objects but also with sufficient background rejection.

Figure 2.5 shows the cut-away view of the ATLAS detector. The detector is designed to be forward-backward symmetric with respect to the interaction point. An inner detector, electromagnetic and hadronic calorimeters, and a muon spectrometer are contained.

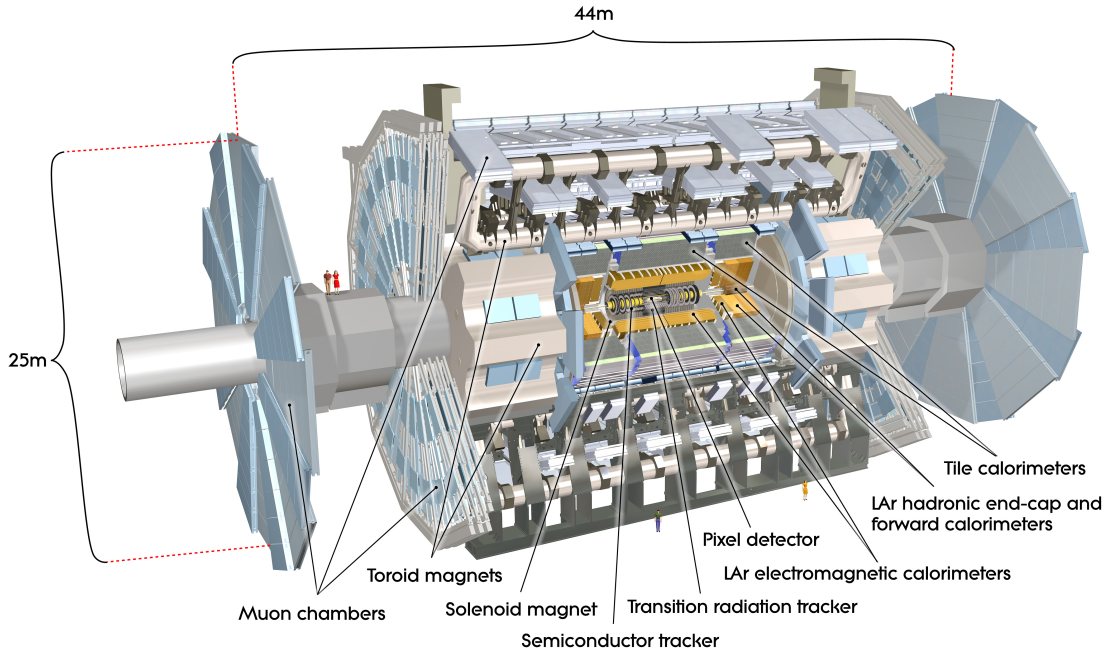


Fig. 2.5: Cut-away view of the ATLAS detector showing its components.

The inner detector is surrounded by the superconducting solenoid with 2T field. To achieve the pattern recognition, vertex and momentum measurements, and electron identification, a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume is used.

Three large superconducting toroid system including one barrel and two end-caps are arranged with an 8 times azimuth symmetrically around the calorimeters. The electromagnetic (EM) calorimeter is composed of high granularity liquid-argon (LAr) sampling calorimeters. It gives an excellent performance in terms of the resolution of energy and position, covering the pseudorapidity range $|\eta| < 3.2$. A scintillator-tile-based hadronic calorimeter provides the coverage of the range $|\eta| < 1.7$, including a central barrel and two extended barrel cylinders, one on either side of the barrel. For the hadronic calorimeters, the LAr technology is also used in end-cap region to extend the pseudorapidity coverage to $|\eta| = 4.9$.

The calorimeter system is surrounded by the muon spectrometer. The toroid system with air-core is used to generate strong bending power, including a long barrel and two end-cap magnets within a relatively light and open structure with multiple-scattering effects minimized. Three layers of high precision tracking chambers give a good muon momentum resolution. The trigger chambers with timing resolution of the order of 1.5-4 ns are also the key components in the muon system. In the end, the overall dimensions of the ATLAS detector is defined by the muon spectrometer.

As for the trigger system, due to the fact that the interaction rate of the LHC pp collisions at the design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ is approximately 1 GHz, and higher as the peak luminosity has already doubled during Run 2. While the event data recording is limited to 400-1000 Hz in Run 1 and Run 2. It thereby requires the trigger system to reject minimum-bias events while maintains maximum efficiency for the new physics. After the trigger system upgrade during the Long Shutdown 1 (LS1), to fit the ATLAS detector readout capability, the maximum L1 rate to 100 kHz, and an average HLT output rate to 1 kHz.

The general performance goal of the ATLAS detector can be found in Table 2.2. The detailed introduction of each sub-system of the ATLAS detector will be introduced in the following subsections.

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	$< 2.5 $	
EM calorimetry	$\sigma_E/E = 10\%\sqrt{E} \oplus 0.7\%$	$< 3.2 $	$< 2.5 $
Hadronic calorimetry (jets) barrel and end-cap forward	$\sigma_E/E = 50\%\sqrt{E} \oplus 3\%$ $\sigma_E/E = 100\%\sqrt{E} \oplus 10\%$	$< 3.2 $ $3.1 < \eta < 4.9$	$< 3.2 $ $3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 0.05\%$ at $p_T = 1$ TeV	$< 2.7 $	$< 2.4 $

Table. 2.2: General performance goals of the ATLAS detector

2.2.2 Magnet system

Four large superconducting magnets form the unique ATLAS hybrid Magnet system, 22 m in diameter and 26 m in length.

Figure 2.6 shows the layout of the magnet system. A volume of approximately 12000 m^3 is filled with the magnetic field provided by the four superconducting magnets. Four main layers of detectors are contained inside. A solenoid which provides a 2 T axial magnetic field for the inner detector, is aligned on the beam axis. A barrel toroid and two end-cap toroids are the other three components which produce a toroidal magnetic field of approximately 0.5 T and 1 T for the muon detectors in the central and end-cap regions, respectively.

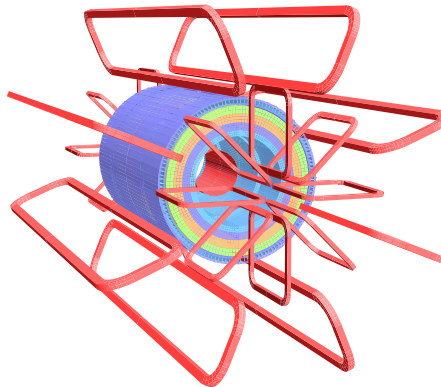


Fig. 2.6: Geometry of magnet windings and tile calorimeter steel. The solenoid winding lies inside the calorimeter volume. The eight barrel toroid coils, with the end-cap coils are shown. The tile calorimeter shown inside is modelled by four layers with different magnetic properties, plus an outside return yoke.

The central solenoid is designed to provide a 2 T axial field. Various properties

are designed to achieve the calorimeter performance. For example, the layout was optimised in order to have a low material thickness in front of the calorimeter. The solenoid windings and LAr calorimeter also share a common vacuum vessel to prevent the use of two vacuum walls. What's more, a 2-mm-thick aluminium heat shield panel is integrated between the inner wall of the cryostat and the solenoid. The solenoid is charged and discharged in about 30 min. In the case of a quench, the energy stored can be safely absorbed.

the magnetic field provided by the barrel toroid fills the cylindrical volume surrounding the calorimeters and both end-cap toroids. It is composed of eight coils encased in vacuum stainless-steel vessels. The total size of the barrel toroid system is 25.3 meters in length, with inner and outer diameters of 9.4 meters and 20.1 meters, respectively. The conductor and coil-winding technology is based on winding a pure Al-stabilised Nb/Ti/Cu conductor into pancake-shaped coils, followed by vacuum impregnation, which is essentially the same for the barrel and end-cap toroids.

A magnetic field to optimise the bending power in the muon spectrometer system end-cap regions is generated by the two set of end-cap toroids. They can slide along the central rails, which is used to open the detector for access and maintenance. Each end-cap toroid is composed of a single cold mass constructed from eight flat and square coil units, and eight keystone wedges, which is stable under the Lorentz forces.

2.2.3 Inner detector

Charged-particle tracks and vertices are reconstructed using information from the inner detector (ID). Three sub-detectors are included in the inner detector: At inner radii, silicon pixel detector and silicon microstrip (SCT) layers provide the high-resolution pattern recognition capabilities. At larger radii, the transition radiation tracker (TRT) comprises many layers of xenon-based mixture gaseous straw tube elements interleaved with transition radiation material and provides continuous tracking to improve the pattern recognition and the momentum resolution. The inner detector is within a cylindrical envelope of radius 1150 mm and of length ± 3512 mm, within a 2 T solenoidal magnetic field. The cut-away view of the inner detector is shown in Figure 2.7.

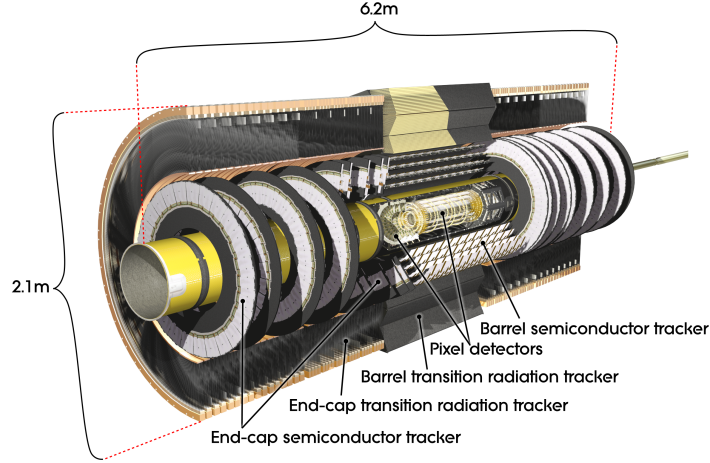


Fig. 2.7: Cut-away view of the ATLAS inner detectors.

Figures 2.8 shows the sensors and structural elements traversed by 10 GeV charged particles in respectively the barrel and end-cap regions.

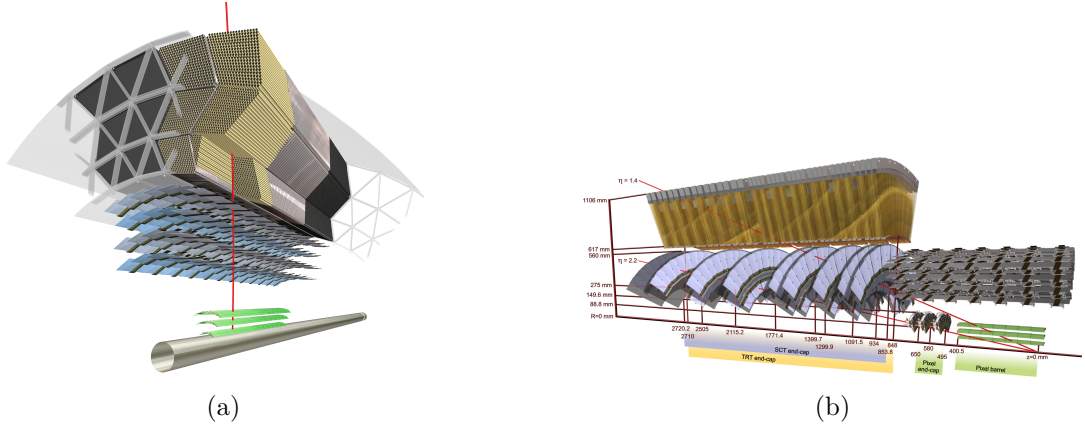


Fig. 2.8: (a) Barrel inner detector: Sensors and structural elements traversed by a 10 GeV p_T charged track. (b) End-cap inner detector: Sensors and structural elements traversed by two 10 GeV p_T charged tracks.

The tracking information provided by the inner detector is important for many Higgs boson-related analysis. The $H \rightarrow \gamma\gamma$ analysis requires separating electrons from photon conversions accurately. The $H \rightarrow ZZ^{(*)}$ and $H \rightarrow WW^{(*)}$ channels ask for a good performance on lepton reconstruction and identification. The momentum measurement of high- p_T muons is also important for those channels. Using track information to distinguish τ -lepton and b -quarks from other objects plays the crucial role in the $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ channels.

2.2.3.1 Pixel detector

The silicon pixel detector (with insertable B-layer [21] installed before the start of Run 2) is the innermost element of the Inner Detector. Four concentric layers distributed at the radii 33 mm, 50.5 mm, 88.5 mm and 122.5 mm from the

beam axis, and three disks on each end-cap are included, with a total of over 1744 modules distributed in $R - \phi$ and z planes, each measuring 2 cm by 6 cm. The detecting material is silicon with a thickness of 250 μm .

There are about 80.4 million readout channels for pixel detectors in total. (67 million for barrel and 13 million for end-caps) covering an area around 1.7 m^2 , taking up around 50% of the readout channels of the ATLAS experiment in total. 16 readout chips and other electronic components are contained by each Pixel module. A pixel with a size of 50 by 400 μm is the smallest unit that can be read out; there are roughly 47,000 pixels per module. It gives resolution around 10 μm in the $R - \phi$ plane and 115 μm in the z plane. The extremely precise tracking very close to the interaction point provided by the pixel detector can help with the identification and reconstruction of secondary vertices from the particles decays like hadrons containing b -quarks or τ -leptons.

2.2.3.2 Semi-Conductor Tracker

The Semi-Conductor Tracker (SCT) is the intermediate element of the inner detector. The concepts and functions of SCT are similar to the Pixel Detector, but have longer, narrower strips rather than smaller pixels, making the coverage larger. It consists of four cylindrical layers of silicon strips at the barrel region, and nine disks each side at the end-caps. A total area of 61 square meters covering radial regions from 30 to 52 cm and $|\eta|$ up to 2.5. The detecting material is silicon wafers with a thickness of 285 μm . 6.3 million readout channels are included in the system.

Each strip has size of 80 μm by 12 cm. For basic tracking in the plane perpendicular to the beam, the SCT is the most critical part of the inner detector as it gives the measurement of particles in a much larger area than the Pixel Detector, with more sampled points. The resolution per module in the barrel are 17 μm ($R - \phi$) and 580 μm (z). While for end-cap disks, they are 17 μm ($R - \phi$) and 580 μm (R).

2.2.3.3 Transition radiation tracker

The outermost component of ID is the transition radiation tracker (TRT). It consists of a straw tracker and a transition radiation detector. The thin-walled proportional drift tubes (straws) are the detecting elements, with a size of 4 mm in diameter, and 144 and 37 cm long in barrel and end-caps, respectively. A voltage about $-1,500$ V, which produce a current pulse (signal) in the wire by driving the negative ions inside straw to a fine wire down the center of each straw, is applied to straws. When a charged particle passes through, the carbon dioxide, oxygen and xenon-mixed gas filled in each straw becomes ionized, then hits are made by

the wires with signals giving it possibilities to determine the path of the particle.

The TRT consists of 52,544 straws segmented to 73 layers in the barrel region, and 122,880 straws distributed to 160 layers in each side of end-caps, as well as 351,000 readout channels. The TRT detector provides a relatively large number of hits (typically 36 per track). The tracking position resolution for TRT system is about $130\ \mu\text{m}$, offering transition radiation detection capability on the R - ϕ plane, and giving additional tracking and important discrimination between electrons and charged hadrons for the region of $|\eta| < 2.0$.

2.2.4 Calorimeters

The electro-magnetic energy measurements are provided by the ATLAS calorimeter system located outside the solenoidal magnet surrounding the Inner Detector. Two basic calorimeter systems are contained inside to cover the full ϕ and $|\eta| < 4.9$ region: an inner electromagnetic calorimeter (ECAL) and an outer hadronic sampling calorimeter (HCAL). With the help from the tracking system, the fine granularity ECAL provides ideal precision measuring electrons and photons. At the same time, the energy of hadrons are absorbed by high-density metal in HCAL to periodically sample the shape of the resulting particle shower, and to infer the energy of the original particle, providing information for jet reconstruction and $E_{\text{T}}^{\text{miss}}$ measurement. Figure 2.9 shows the cut-away view of the ATLAS calorimeter.

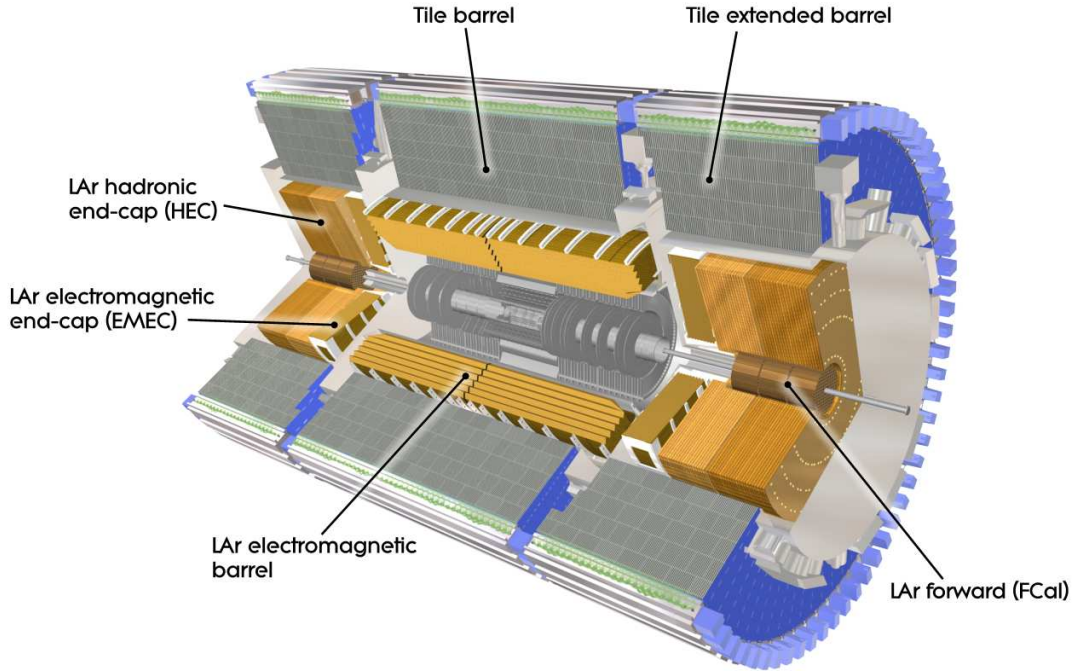


Fig. 2.9: Cut-away view of the ATLAS calorimeter.

The EM calorimeters are based on liquid argon detector, while the hadronic

calorimeters adopts the scintillating tiles and steels as the active material in the barrel, and also uses the liquid argon technology in the forward region. The schematic view of ECAL and HCAL module can be found in Figure 2.10. Details are described in the following subsections.

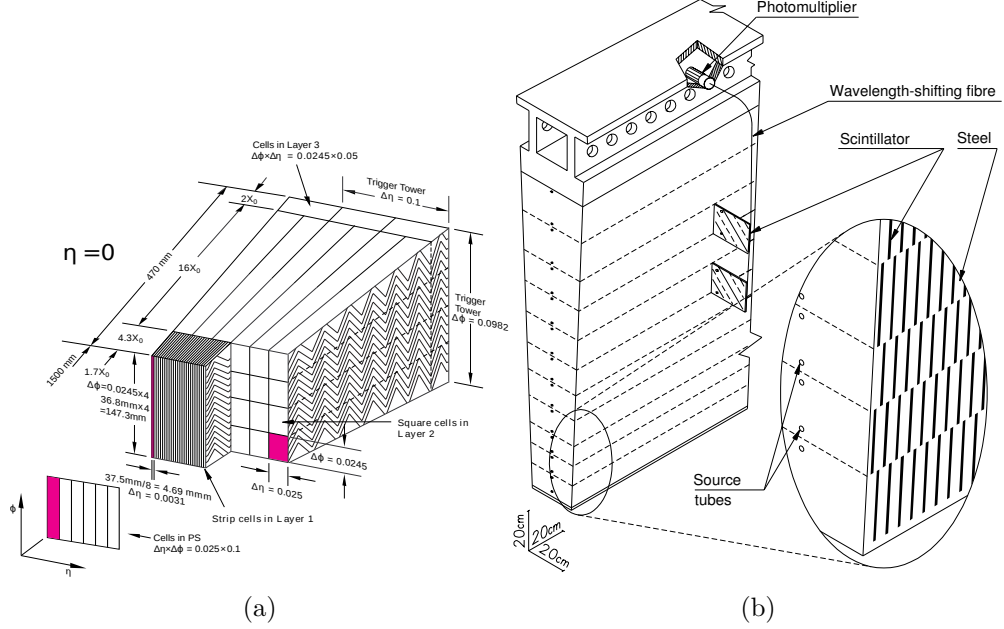


Fig. 2.10: (a) Schematic view of an ECAL barrel module where the different layers are indicated. (b) Schematic showing the mechanical assembly and the optical readout of the hadronic tile calorimeter are integrated together.

2.2.4.1 LAr electromagnetic calorimeter

The energy from particles that interact electromagnetically, including charged particles and photons, is absorbed by the electromagnetic (EM) calorimeter. It is a lead/liquid-argon (LAr) sampling calorimeter, which has accordion-shaped electrodes to be able to provide ϕ symmetry without azimuthal cracks. The energy-absorbing materials are stainless steel and lead. It contains the barrel section covering the pseudorapidity region $|\eta| < 1.475$, and two end-cap sections, covering $1.375 < |\eta| < 3.2$. There are three layers divided longitudinally in depth for $|\eta| < 2.5$, and two layers for $2.5 < |\eta| < 3.2$. In the regions $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$, the first layer with a depth of 4.3 radiation lengths, has a fine η segmentation used to discriminate isolated photons from pairs of close-by photons decayed from neutral hadrons. The second layer is with a depth of 16 radiation lengths, where most of the energy is collected. The information collected from the cluster barycenter of the second layer allows a measurement of shower directions without assumptions on the production points of photons. There is back layers with a depth of 2 radiation lengths and with coarse granularity to collect the end

of showers. In the region of $|\eta| < 1.8$ a presampler layer allows corrections to be made for energy losses upstream of the calorimeter. The presampler contains an active LAr layer of thickness 1.1 cm in the barrel and 0.5 cm in the end-cap region, respectively. In addition, Cryostats are also installed around the EM calorimeter to control the temperature.

2.2.4.2 Hadronic calorimeters

For these particles passing through the electromagnetic calorimeter, but do not interact via the strong force, which are primarily hadrons, the energy is absorbed and the hadronic shower is defeated by the hadron calorimeter. The steel absorbers and scintillator tiles are used in the barrel region, or either copper in the end-cap region as the absorbers of the liquid-argon hadronic end-cap calorimeter (HEC), or copper-tungsten as the absorbers of liquid-argon forward calorimeter in the forward region (FCal). Both the HEC and FCal are immersed in an LAr active medium.

The HCAL is large and consists of a huge amount of construction material. The tile calorimeter is 8 m in diameter and 12 m along the beam axis, covering $|\eta| < 1.7$ region. It is a sampling calorimeter just outside the ECAL. It consists of a central barrel in the region $|\eta| < 1.0$ with a 5.8 m length, and two extended barrel in the region $0.8 < |\eta| < 1.7$ with 2.6 m lengths, spanning radii from 2.28 m to 4.25 m. The tile calorimeter uses steel as absorber and scintillating tiles as active material distributed over 64 modules. Both the barrel and extended barrels are separated into three layers. For barrel, the thickness are approximately 1.5, 4.1 and 1.8 interaction lengths (Λ) for the three layers, while they are 1.5, 2.6 and 3.3 for two extended barrels. At $\eta = 0$, the total detector thickness of the tile-instrumented region at the outer edge is 9.7 Λ . Two separate photomultiplier tubes (PMT) are used to read out each scintillating tile through wavelength shifting fibers.

The HEC covers $1.5 < |\eta| < 3.2$ and consists of two independent wheels (one front wheel and one rear wheel) with a total of four layers per end-cap. It is composed of 32 wedge-shaped modules with copper absorbers. It distributes directly behind the end-cap ECAL and shares the same LAr cryostats. It overlaps with both the tile calorimeters and the FCal in order to minimize the drop in material density at the transition area. The resulting sampling fractions for the front wheel and the rear wheel are 4.4% and 2.2% respectively.

The Forward Calorimeter (FCal) is in the same cryostats as the HEC and extends the coverage to $3.1 < |\eta| < 4.9$. The FCal has an interaction length of approximately 10 Λ deep. It consists of three modules in each end-cap with a 45 cm depth, all using LAr as active medium. The first module uses copper as

absorbers and is optimized for EM measurements, while the other two using tungsten measure predominantly the energy of hadronic interactions. The structure with a very small liquid-argon gap is used, which are designed by applying an electrode structure of small-diameter rods oriented parallel to the beam direction. As the FCal modules are located at very forward region with high η , at a distance of approximately 4.7 m from the IP, with high particle fluxes.

2.2.5 Muon spectrometer

There is a muon spectrometer surrounding the calorimeter. It comprises precision tracking chambers ($|\eta| < 2.7$) and separate trigger ($|\eta| < 2.4$) in the magnetic field provided by three large toroids. The Muon Spectrometer is the outer part of the ATLAS detector, consisting of three parts: (1) An approximately 1.0 to 7.5 T magnetic field giving the magnetic deflection of muon tracks, provided by three toroidal magnets. The central magnetic field is provided by the large barrel toroid in the range $|\eta| < 1.4$. For $1.6 < |\eta| < 2.7$, it is from two smaller end-cap magnets. A combination of barrel and end-cap fields provides the magnetic deflection in the transition region $1.4 < |\eta| < 1.6$. (2) A set of 1200 chambers measuring tracks of the outgoing muons with high spatial precision, with p_T ranging from around 3 GeV to 3 TeV. The designed momentum resolution of the standalone measurement is 3% at 100 GeV and 10% at 1 TeV. (3) A set of triggering chambers with good time-resolution. The extent of the muon spectrometer starts at a radius of 4.25 m close to the calorimeters out to 11m which is the full radius of the detector. Figure 2.11 shows the cut-away view of the muon spectrometer.

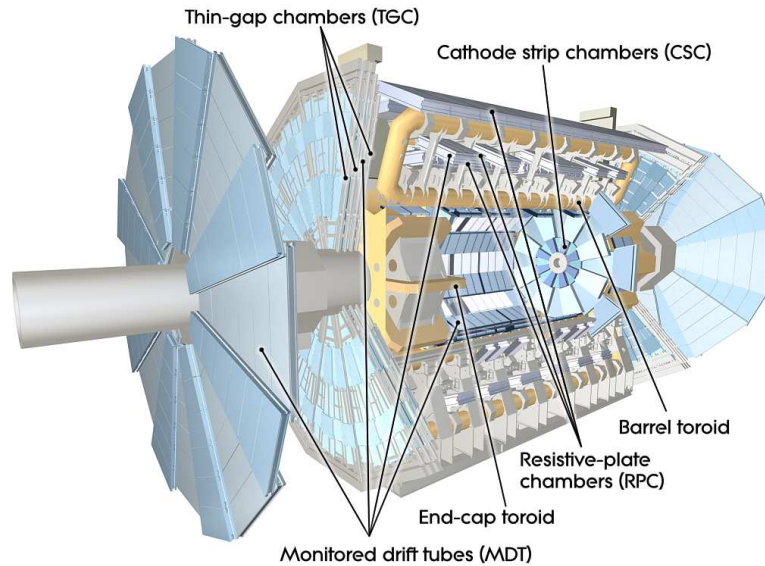


Fig. 2.11: Cut-away view of the ATLAS Muon-system.

Figure 2.12 shows the schematic view of a quarter-section indicating the lay-

out of each component. There are roughly one million readout channels included. The total area of its layers is around 12,000 m².

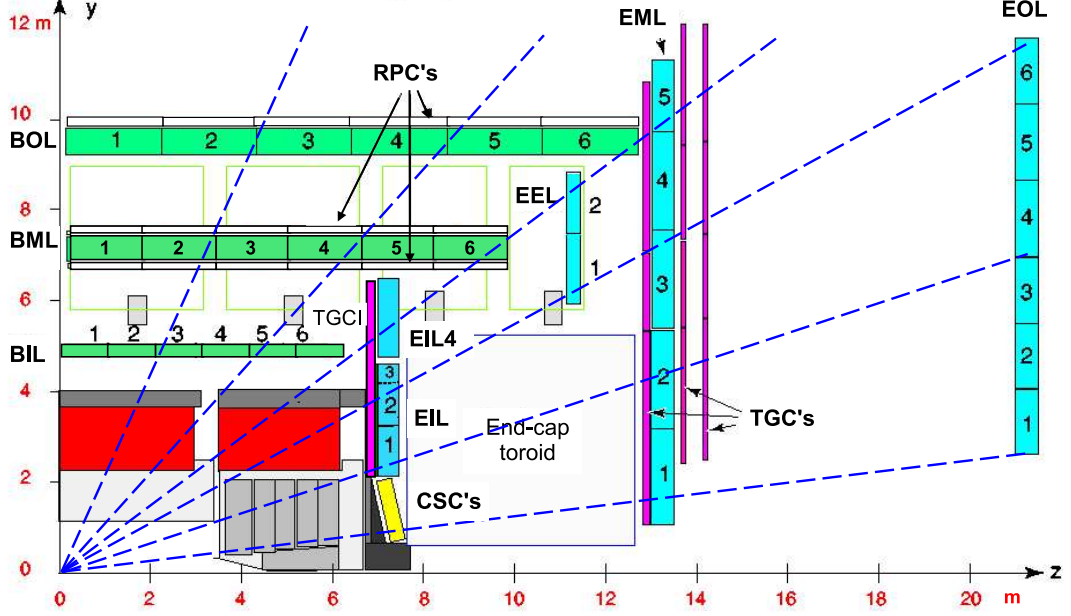


Fig. 2.12: Cross-section view of the whole muon system in a plane containing the beam axis.

2.2.5.1 Monitored Drift Tubes (MDT)

The precision tracking chambers providing the momentum measurement are mainly MDTs. In the region $|\eta| < 2.7$ except the innermost end-cap layer where MDTs cover $|\eta| < 2.0$, three to eight layers of 1 m to 6 m long aluminum drift tubes, with a diameter of 29.970 mm, are filled with Ar/CO₂ gas at 3 bar with tungsten-rhenium anode. The $|\eta| < 2.0$ region contains three layers of MDTs installed at radii around 5 m, 7.5 m and 10 m. In the end-cap region $2.0 < |\eta| < 2.7$, MDTs are mounted on two large wheels perpendicular to the beam axis, with $|z|$ equal to 14 m and 21.5 m, respectively. The chamber size increases in proportion of the distance from the IP, which achieves an average resolution of 35 μm per chamber, and 80 μm per tube.

2.2.5.2 Cathode Strip Chambers (CSC)

Cathode Strip Chambers (CSC) is another component of the precision tracking system. They are trapezium-shaped multiwire proportional chambers, with two cathode strips segmented into strips in orthogonal directions per plane, which offer higher rate capability and good time resolution to be suitable to be distributed in the region nearing the beam axis. CSCs are used in the innermost tracking layer

in the region $2 < |\eta| < 2.7$, $|z| = 7.4$ m. The resolution of a chamber is about $5\text{ }\mu\text{m}$ in the transverse plane and $40\text{ }\mu\text{m}$ in the bending plane due to a coarser cathode segmentation.

2.2.5.3 Resistive Plate Chambers (RPC)

RPCs are gaseous parallel electrode-plane detectors without wires yielding good time and spatial resolution as well as good rate capability. They are used as trigger detectors in the barrel ($|\eta| < 1.05$) and consist of three concentric cylindrical layers (trigger stations) around the beam axis. Each station consists of two independent detector layers measuring transverse coordinates η and ϕ . Two out of three are placed below and above the middle MDT layer, another is outside the precision tracking system.

2.2.5.4 Thin Gap Chamber (TGC)

TGCs are also multi-wire proportional chambers with good time resolution and high rate capability. Each TGC trigger station contains nine layers, distributed in the end-cap region ($1.05 < |\eta| < 2.4$). There is one station located in front of the innermost tracking layer, one in front of the middle MDT wheel. The other two are behind the middle MDT wheel. Besides trigger, TGCs can also determine the second, azimuthal coordinate to complement the measurement of the MDTs in the bending (radial) direction.

2.2.6 Trigger system

In the LHC Run 2, with the collision energy increasing to 13 TeV, higher luminosity and higher pile-up level lead to an increase of the rate. Comparing to the Run 1, trigger rate increases by a factor up to 5. An upgrade two-level trigger system [22] was used during the $\sqrt{s} = 13$ TeV data-taking period. The schematic plot of the ATLAS Trigger and DAQ system in Run 2 is shown in Figure 2.13.

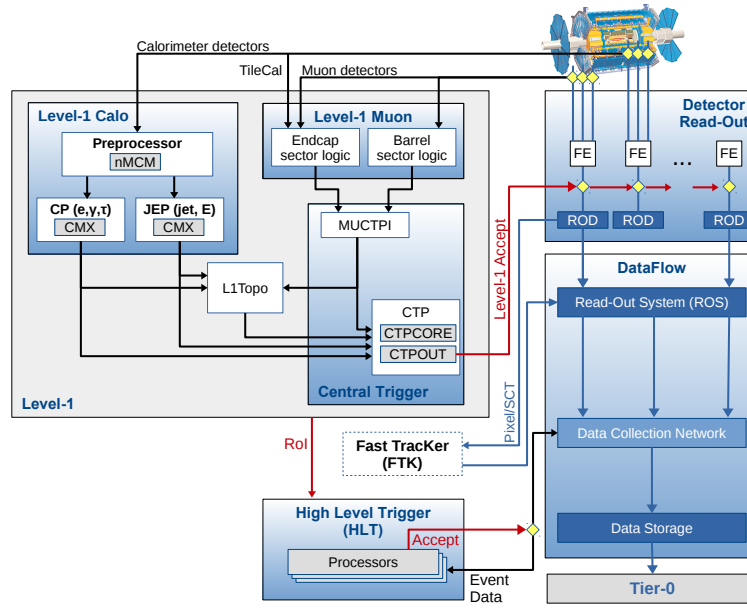


Fig. 2.13: Schematic of the ATLAS Trigger and Data Acquisition system in Run 2. The components of the L1 Trigger system are shown in detail.

Dedicated hardware implements the first-level (L1) trigger selection, with only a subset of the detector information used and the event rate is reduced to at most 100 kHz. Events meeting the L1 requirements are then processed by a high-level trigger executing algorithms on a computer farm. The algorithms are similar to those in the offline reconstruction software, which can reduce the event rate to approximately 1 kHz. Figure 2.14 illustrates the expected peak rates and bandwidths through each component.

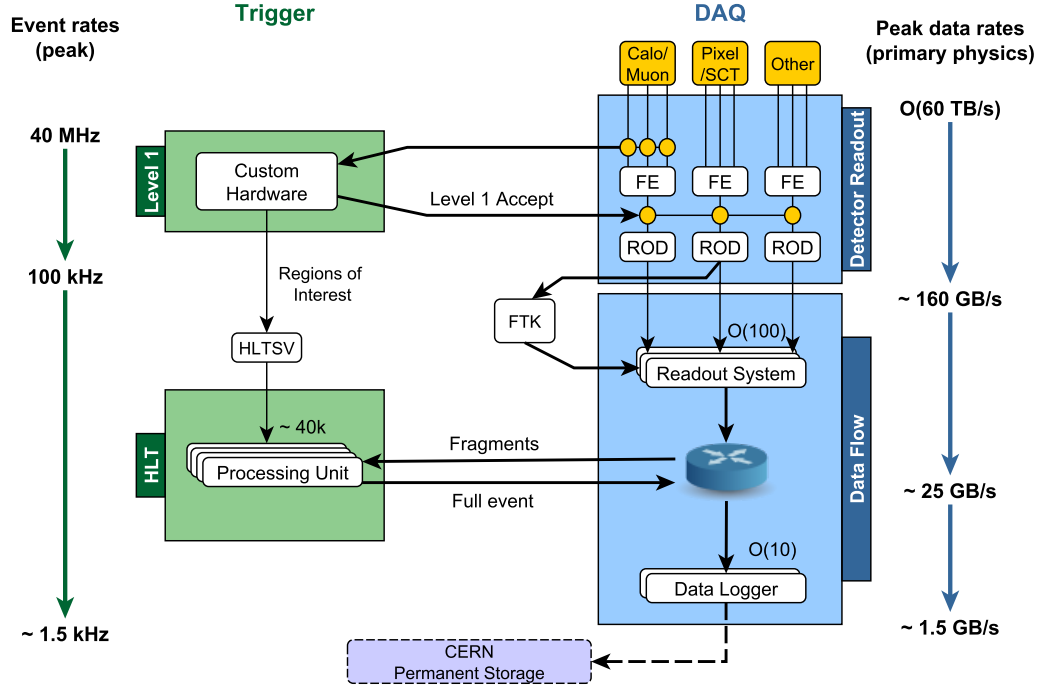


Fig. 2.14: Functional diagram of the ATLAS Trigger and Data Acquisition system in Run 2 showing expected peak rates and bandwidths through each component.

2.2.6.1 Level-1 Trigger (L1)

Upgrades of the ATLAS Level-1 trigger hardware and the detector readout have been implemented for Run 2 data taking. The maximum Level-1 trigger rate is allowed to raise to 100 kHz in Run 2, which is significantly higher than Run 1 (70 kHz).

The reduced granularity information from both the electromagnetic and hadronic calorimeters are used by the Level-1 calorimeter trigger to identify an Region-of-Interest (RoI). With the different algorithm and predefined transverse energy threshold, photons, electrons, taus and jets, as well as total and missing transverse energy (E_T^{miss}) are searched. In Run 2, the Level-1 Calorimeter trigger has upgraded its new Multi-Chip Modules (nMCM) to field-programmable gate array (FPGA) technology from the previous application-specific integrated circuits (ASICs) used in Run 1. It allows to flexibly use a new bunch-by-bunch dynamic pedestal correction and auto-correlation filters to suppress pile-up effects.

The Level-1 fast muon trigger signal is provided by the Level-1 Muon trigger system, which consists of a barrel RPC section and two TGC endcap sections, as described before in Section 2.2.5. The Run 2 upgrades were applied to the Level-1 Muon trigger based on the experience of Run 1 data taking. To suppress most of

the fake muon triggers caused by particles not originated from IP, a coincidence with hits from the innermost muon chambers is required by the muon endcap trigger ($1.05 < |\eta| < 2.4$). The L1 MU15 rate is reduced by approximately 50% in the $1.3 < |\eta| < 1.9$ region that corresponds a very small signal efficiency loss of only 2%. Similarly, in $1.05 < |\eta| < 1.3$ region, a coincidence logic is applied using the outermost layer of the hadronic Tile Calorimeter in order to reject the background particles.

2.2.6.2 High-level Trigger (HLT)

The RoI information from the L1 is transferred to the HLT, used for regional reconstruction in the trigger algorithms. Events accepted by the HLT are then processed with the offline reconstruction.

In Run 1 the ATLAS trigger system had separate Level-2 (L2) and Event Filter (EF) computer clusters. For Run 2, the L2 and EF have been merged into a single event processing HLT farm, which allows for dynamic resource sharing between algorithms and reduces the complexity for both hardware and software.

To minimize differences between the HLT and the offline analysis selections, most of the trigger reconstruction algorithms are re-optimized, which gives a significant performance improvement in some cases. For instance, the inefficiencies are reduced by more than a factor two in the hadronic tau triggers. Some triggers are augmented to also allow aggregation of the RoIs into a single object To reduce the computing resources usage of events with a large multiplicity of partially overlapping RoIs. Comparing to the LHC Run 1, the average output rate of the HLT has been increased from 400 Hz to 1000 Hz.

CHAPTER 3

Simulation and event reconstruction

During proton–proton collisions at the LHC Run 2, beam bunches crossed every 25 ns and produced on average around 34 collisions per bunch crossing. The ATLAS detector is designed to keep the most interesting interactions for physics analyses, resulting in stringent challenges to the event reconstruction. To study the detector response for many different physics processes and scenarios, Monte Carlo event simulation is one of the essential tool bridging the gap between the complex detector signatures and observed data.

In the ATLAS experiment, a simulation system [23] has been implemented into the ATLAS software framework called Athena [24], which carries events from the event generation to output in a format which is identical to that of data. The Geant4 simulation toolkit [25, 26] is also integrated in the work flow. Figure 3.1 shows the flow of the ATLAS simulation and reconstruction software. The detailed event simulation and reconstruction will be discussed further in the following sections.

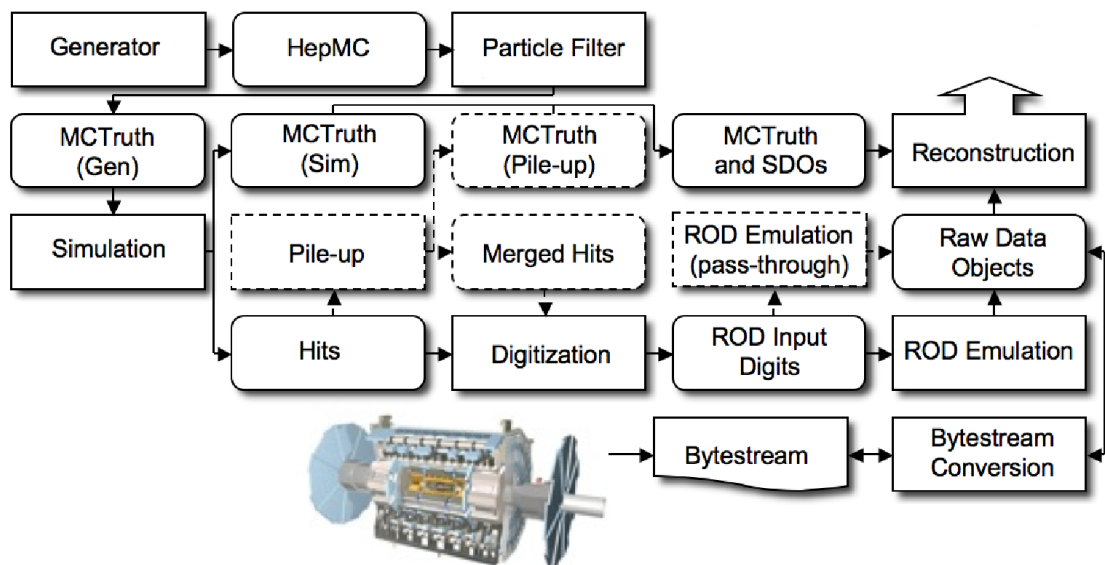


Fig. 3.1: Flowchart of the ATLAS simulation software, from event generators through reconstruction.

3.1 Event simulation

The ATLAS event simulation chain is generally divided into three steps: generation of the event and immediate decays, simulation of the detector response, and digitization of the energy deposited in the different regions of the detector into currents and voltages to emulate the readout of the ATLAS detector. Either the format identical to the ATLAS data acquisition system (DAQ) output, or an object-based format can be used to store the simulation chain results. Thus, both the real data and simulation from the detector can then be processed through the same ATLAS trigger and reconstruction packages.

3.1.1 Monte-Carlo generation

Monte Carlo generators provide fully exclusive simulations of high-energy collisions. Generators are run within Athena framework and the generated event output is put into a transient store, in HepMC format. The generated particles with a short lifetime are decayed within the generation process without considering the interactions with the detector. The “stable” particles with a long lifetime ($c\tau > 10$ mm) are stored and expected to propagate through a part of the detector. Dedicated filters can be applied on events during the generation process targeting a certain property (e.g. semi-leptonic or dilepton decay modes for $t\bar{t}$ events).

3.1.2 Simulation

Geant4 [25, 26] is the standard particle simulation toolkit of ATLAS, which provides physic models and infrastructure for particle transportation through a geometry constructed in its own format. Events generated in the last step are propagated through the ATLAS detector geometry by Geant4. Cuts and transformations can then be made to the event such as smearing the vertex position, defining the $\eta - \phi$ range which primary particles passed through to be simulated. The output of this step is stored in HITs format, containing some metadata describing the configuration of the simulation during the run, a collection of hits for each subdetector and all truth information requested. To achieve the required simulated statistics for many physics studies, different fast simulation programs have been developed to simplify the Geant4 simulation by using pre-simulated showers stored in memory to replace low energy electromagnetic particles from the calorimeter, such as ATLFAST-I and ATLFAST-II.

3.1.3 Digitization

The HITS file produced in the last step can then be converted into detector response “digits” by the ATLAS digitization software. A digit is produced when the current or voltage on a particular readout channel rises above a pre-defined threshold within a particular time window. The peculiarities of each subdetectors are modelled in digitization step, as well as many inelastic, non-diffractive proton-proton interactions, beam halo and beam gas interactions. The digits are mainly written out as Raw Data Objects (RDOs) format, and can also save as Simulated Data Objects (SDOs) to determining tracking efficiency and fake track rates.

3.2 Event reconstruction

Figure 3.2 shows the data flow in the ATLAS experiment. The data from the detector filtered by the Trigger system are sent to the Tier-0 computer center for initial processing by the offline reconstruction software. A small amount of data called “express stream” is sent to to be processed in quasi real time for running the complete reconstruction and monitoring chain. Data quality is monitored online at the trigger level as well as offline during reconstruction. Dedicated data streams are written out at the trigger level to allow for detector alignment and calibration. The calibration centers perform a first alignment and calibration within 24 hours after data taking. The obtained calibration constants are used for the bulk processing of the data. At the end of the reconstruction chain the data are distributed to the Tier-1 and Tier-2 centers which are used for analysis and production of simulated data. The following sub-sections will describe the reconstruction algorithms of the physics objects, such as vertices, tracks, photons, electrons, muons, jets and E_T^{miss} .

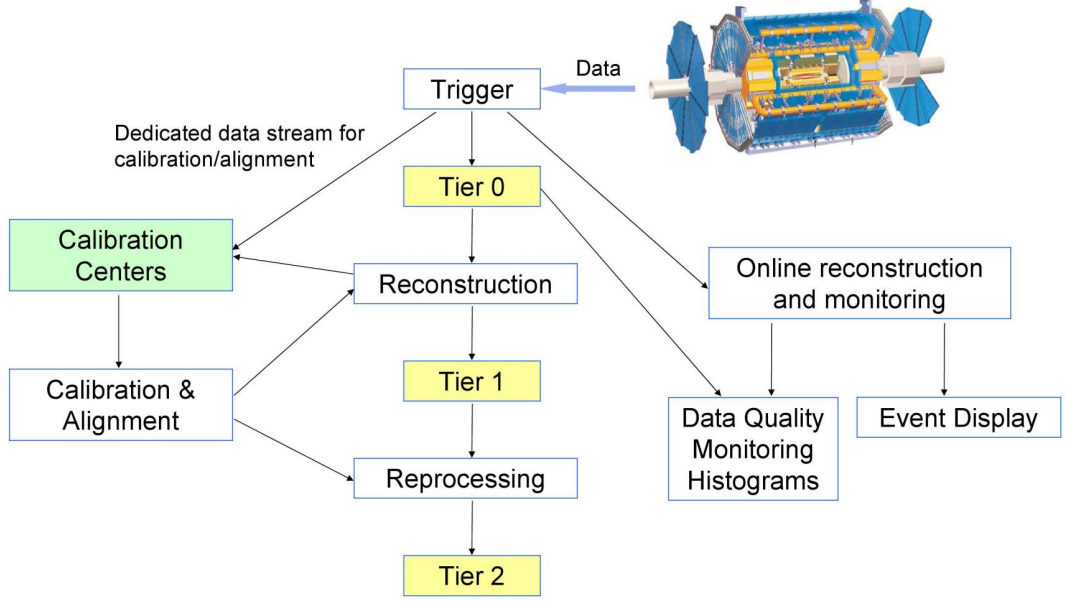


Fig. 3.2: Flowchart of the ATLAS data.

3.2.1 Photons

In the the $H \rightarrow \gamma\gamma$ analysis (Chapter 4), all events in are preselected by requiring at least two photon candidates. The photon reconstruction, calibration, identification and isolation in the ATLAS experiment are discussed in this subsection.

3.2.1.1 Photon reconstruction and calibration

The energy deposits (clusters) in the EM calorimeters, with a size of $\Delta\phi \times \Delta\eta = 0.125 \times 0.075$ and with the total transverse energy E_T at least 2.5 GeV [27] are used as seeds for the photon reconstruction in the ATLAS detector by a sliding-window algorithm. To distinguish photons and electrons, and also to classify unconverted and converted photons, a reconstruction algorithm is developed by looking at possible matches between energy deposits and tracks reconstructed in the inner detector and extrapolated to the calorimeter. If a conversion vertex is reconstructed and the matched track(s) is consistent with originating from a photon conversion process, the corresponding candidates are considered as converted photons. Converted photons are classified as single-track or double-track conversions depending on the number of assigned tracks. Clusters without matching tracks are classified as unconverted photon candidates.

An electromagnetic cluster belonging to the converted and unconverted photons is used to measure the energy of candidates. The cluster is with a size of $\Delta\phi \times \Delta\eta = 0.175 \times 0.075$ in the barrel region, and $\Delta\phi \times \Delta\eta = 0.125 \times 0.125$ in

endcaps.

A combination of data-driven and simulation-based correction factors [28] are used to correct the cluster electromagnetic energy for energy losses in the inactive material in front of the calorimeter. The converted and unconverted photon candidates are applied with different correction factors.

Figure 3.3 shows the energy resolution $\sigma_{E_{calib}}/\sigma_{E_{gen}}$ estimated from the interquartile range of E_{calib}/E_{gen} as a function of $|\eta|$ for converted and unconverted photons.

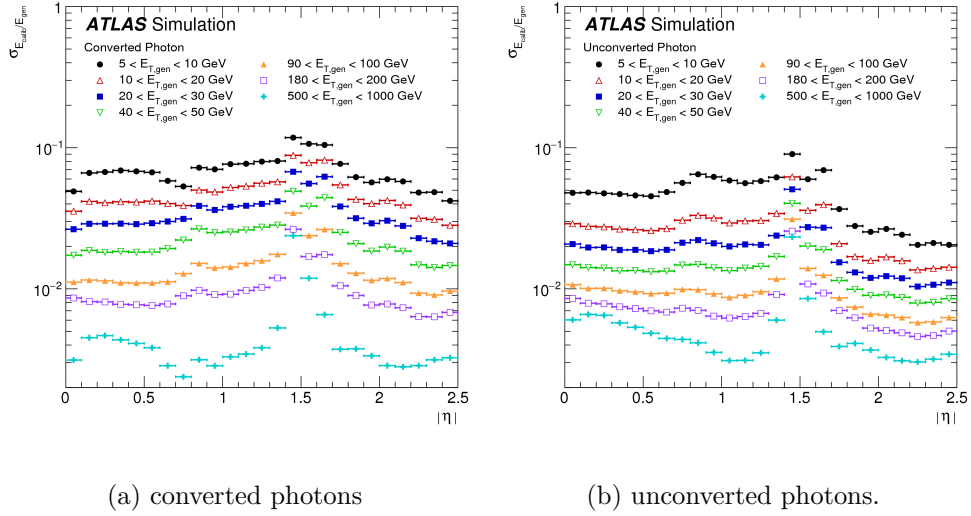


Fig. 3.3: Energy resolution $\sigma_{E_{calib}}/\sigma_{E_{gen}}$ estimated from the interquartile range of E_{calib}/E_{gen} as a function of $|\eta|$.

3.2.1.2 Photon identification and isolation

To reduce the background contamination primarily the photon pairs decayed from neutral hadrons in jets, a set of identification criteria are applied to photon candidates, based on the longitudinal and lateral electromagnetic shower shape in the calorimeter [29]. To fulfill the identification requirement, only a small fraction of energy of photon candidates deposits in the hadronic calorimeter, and the lateral shower shape should be consistent with that expected from a single electromagnetic shower. Prompt photons typically produce narrower energy profiles in the EM calorimeter and have smaller leakages to the hadronic calorimeter compared with background jets. Two reference selections are used: a loose criterion, based on information only from the second layer of the EM calorimeter and the hadronic calorimeter, primarily used for purposes such as triggering and preselections, and a tight criterion, with additional information from the fine segmentation of the first layer of the EM calorimeter. The tight selection requirements are specially tuned for converted and unconverted photon candidates.

To take into account the small differences between data and simulation, corrections are applied to the electromagnetic shower shape variables of simulated photons. Correction factors as a function of conversion type, η and E_T are calculated to correct for the residual mismatch between the efficiency measured in the data and in the simulation. Figure 3.4 shows the comparison of the data-driven measurements of the identification efficiency for photons as a function of E_T in the central region.

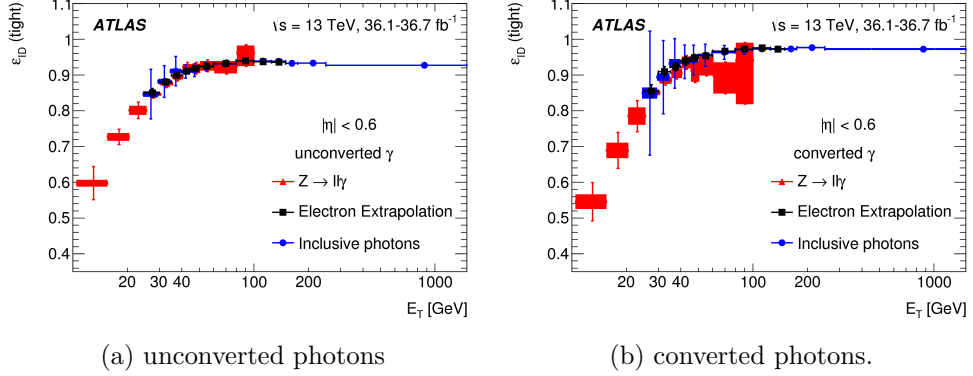


Fig. 3.4: Comparison of the data-driven measurements of the identification efficiency for photons as a function of E_T , for the pseudorapidity interval $|\eta| < 0.6$.

To reject the hadronic jet background contamination, isolation requirements are applied on photon candidates, using the information from the tracking detector and calorimeters. Two complementary isolation variables can be used based on calorimeter and track information, respectively.

The calorimeter isolation is computed by summing up the transverse energies of positive-energy topological clusters [30] within a cone of $\Delta R = 0.2$ in the calorimeter centered around the photon candidate. Candidates with a calorimeter isolation larger than 6.5% of the photon transverse energy are rejected. To improve the efficiency of the isolation selection for events with high pileup, the track isolation is used based on the scalar sum of the transverse momenta of all tracks in a cone of $\Delta R = 0.2$ with $p_T > 1$ GeV. For converted photon candidates, the conversion-associated tracks are removed. Photon candidates with a track isolation larger than 5% of the transverse energy are rejected. The track isolation efficiency from the inclusive sample in the central region can be found in Figure 3.5

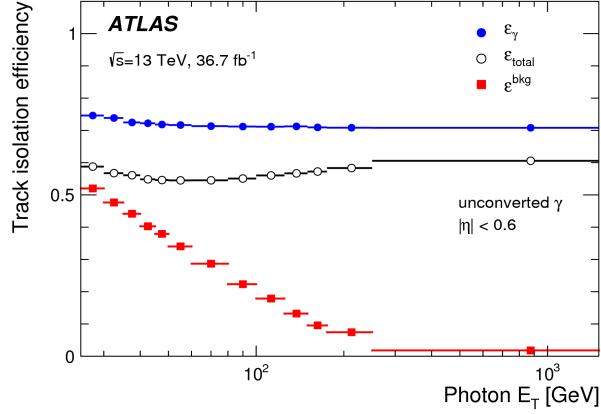


Fig. 3.5: Track isolation efficiency for prompt (blue), fake (red) and all (black) unconverted photons in the region $|\eta| < 0.6$.

3.2.2 Electrons

The reconstruction and the calibration of electrons are similar to photons. A sliding-window algorithm with a size of $\Delta\phi \times \Delta\eta = 0.125 \times 0.075$ is used [31]. The cluster energy is calibrated using a dedicated set of calibration coefficients optimized for electrons then. The reconstructed tracks and interaction vertices in the ID can be matched to an energy deposit are used to find electron candidates, which should be associated with one ID track originating from a vertex in the beam interaction region.

Similarly to photons, the longitudinal and transverse shower profile of clusters, as well as track properties are used in the identification by building up likelihood criteria. In Run 2, the signal acceptance efficiencies for electron candidates with transverse energy 25 GeV are in the range from 78% to 90% and increase as a function of E_T . Finally, the electron candidates must satisfy both the calorimeter and track-based isolation.

3.2.3 Muons

Based on the track information collected from the ID and the MS, as well as the cluster information measured from the calorimeters, different reconstruction algorithms are used to build muon candidates [32]. Tracks reconstructed separately by the ID and the MS are combined by the main algorithm “Combined Muon”. To extend the acceptance region beyond the ID coverage limit to include $2.5 < |\eta| < 2.7$, Extrapolated (ME) muons are reconstructed only based on the MS tracks. What’s more. Segment-tagged (ST) muons are reconstructed with an ID track associating with at least one local segment in the MS, to increase the acceptance for muon candidates with low p_T or falling-into un-instrumented region in the MS.

Calorimeter-tagged (CT) muons are also developed which combine the ID track and energy deposits, which is optimal to central muons with p_T between 15 to 100 GeV. Muons from each algorithm are required to have $p_T > 10$ GeV and $|\eta| < 2.7$. The muon reconstruction efficiency is around 99% for the full acceptance region.

Variables such as the number of hits in the ID and the MS, the p_T difference between the ID and the MS measurements are used to build up muon ID cut to reject background mainly from the light hadron decays. To suppress non-prompt muons, isolation selections are adopted based on track and calorimeter information.

3.2.4 τ -leptons

Leptonic decayed τ -leptons are indistinguishable from prompt electrons and muons, which takes around 35% of the τ decay branching ratio. The remaining 65% hadronically decayed τ -leptons are reconstructed using the ID and the calorimeter information combined in a multivariate discriminant [33]. Quantities describing the shower shape in the calorimeters are used to distinguish between hadronically decaying τ -leptons and jets initiated by quarks or gluons. Electron fakes is rejected by imposing a veto based on the emission of transition radiation and by the measured shower shape in the calorimeter. A BDT-based τ -identification working points are also developed. The resulting identification efficiency at the tight WP stays stable for the whole p_T range, at 45% and 60% for 3-prong and 1-prong τ -leptons, respectively.

3.2.5 Jets

Jets are narrow cones composed of collinearly showers of hadrons, and are prominent features observed in the high energy hadronic colliders. The reconstruction, calibration and jet tagging technique are briefly introduced in this section.

3.2.5.1 Jet reconstruction

ATLAS primarily uses topo-clusters as the inputs to jet reconstruction, where topo-clusters are topologically-grouped noise-suppressed clusters of calorimeter cells. Jets are reconstructed using anti- k_t algorithm [34] with radius parameter $R = 0.4$ typically called small- R jets for representing quarks and gluons, and with $R = 1.0$ for large- R jets representing hadronically decaying massive particles. Overlapped jets within $\Delta R = 0.2$ of an isolated electron or within $\Delta R = 0.4$ of an isolated photon are discarded.

3.2.5.2 Jet energy scale calibration

Fig. 3.6 shows an overview of the calibration chain for the jet calibration procedure consists of many steps [35]. Remove the contribution from pile-up sources is the first step before calibrating, includes correcting the jet axis to point to the hard-scatter vertex of interest (origin correction) and removing the excess energy caused by in-time and out-of-time pile-up. The next step is using MC simulation by comparing reconstructed jets to jets built from simulated particles referred as truth jets to obtain the jet energy scale (JES) calibration factor, as there is a large fraction of the energy in a hadronic shower is invisible to the detector. Finally, an *insitu* calibration can correct for the data vs MC differences by using the well-understood central jets and other objects like muons and electrons to provide correction factors.

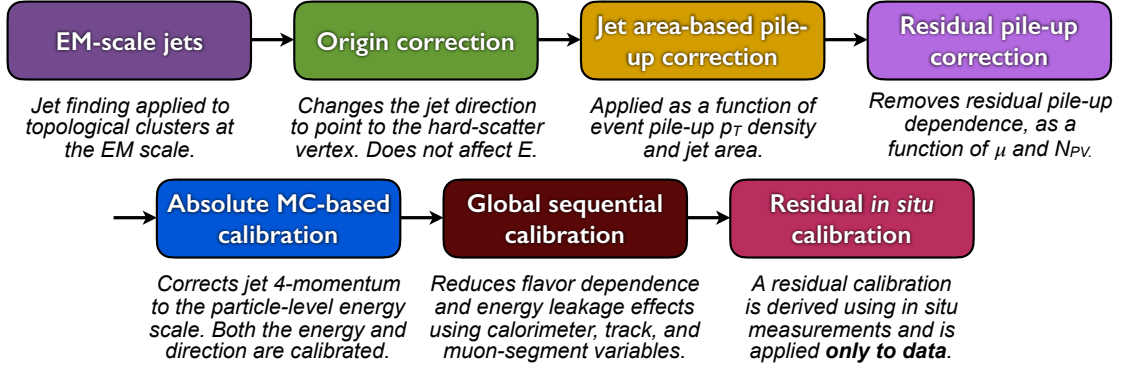


Fig. 3.6: Calibration stages for EM-scale jets. Each stage of the calibration is applied to the four-momentum of the jet other than the origin correction.

3.2.5.3 Jet flavor tagging

The jet substructure is useful in identifying the origin of the jet, and particularly to separate heavy hadronic particles like b -jets from QCD dijet/multijet production.

To identify jets containing a b -hadron, three b -tagging algorithms consists the impact parameter based algorithm, secondary vertex finding algorithm and decay chain multi-vertex algorithm are combined together in a multivariate discriminant (MV2), which is adopted as the ATLAS default b -tagging algorithm. Four different working points with efficiencies for identifying b -jets of 60%, 70%, 77% and 85% are used in analysis.

Besides, jet substructure variables are used to build Booster Decision Trees (BDTs) and Deep Neural Networks (DNNs) for W -tagging, with a fixed 50% signal efficiency working point, and top-tagger uses a fixed 80% signal efficiency working point. There is also a quark vs gluon tagger mainly uses a Convolutional Neural Network based on jet image representing the track multiplicity and jet width.

3.2.6 Missing transverse energy

The E_T^{miss} is an important signature for many physics processes where neutrinos are involved in the final states. It is an event quantity calculated based on momentum conservation in the transverse plane [36]:

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

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

where $E_{x(y)}^{\text{jets}}, E_{x(y)}^e, E_{x(y)}^\gamma, E_{x(y)}^\tau, E_{x(y)}^\mu$ are the sum of $x(y)$ -component of the momenta of all jets, electrons, photons, taus and muons in the event, respectively. The E_T^{miss} Soft Term, $E_{x(y)}^{ST}$ is the sum of $x(y)$ -component of the momenta of all topo-clusters and tracks not associated to the above physics objects. Several algorithms used to reconstruct the E_T^{miss} soft term using energy deposits or tracks. The default algorithm uses the soft term relied on tracks called Track Soft Term (TST), which is robust against varying pile-up condition, but misses the contribution from neutral particles. The alternative Calorimeter-based Soft Term (CST) contains underlying event activity and soft radiation from the hard event.

Besides E_T^{miss} , a likelihood-based missing transverse momentum significance is evaluated by using simulated samples, to separate events in which the reconstructed E_T^{miss} originates from weakly interacting particles, from those in which E_T^{miss} is consistent with contributions coming from particle measurement, resolution and inefficiencies.

3.2.7 Others

Besides the major physics objects described in the above subsections, other important facts corresponding to the physics analysis in this thesis are summarized here.

The ID tracks consists of two methods to be reconstructed [37]. The first inside-out approach makes use of the high granularity of the SCT and pixel to get prompt tracks from the IP. By combining space points object in the first SCT layer and the pixel layers, track seeds are formed and then extended to form track candidates. Another outside-in approach starts from searching segments in the TRT and extends inwards to add pixel hits.

The primary vertex (PV) is reconstructed with tracks passing a bunch of selection such as p_T , $|\eta|$, number of silicon hits cut. One vertex is defined from fitting all pre-selected tracks [38]. If there are tracks incompatible to be associated with the vertex, a new vertex candidate is seeded by applying the same algorithm

to those tracks. This process won't stop until all available tracks are associated. Then all the vertices with at least two associated tracks are treated as the PV candidates. Generally, the PV with the largest value of $\sum p_T^2$ is used in physics analysis.

The selection of the correct diphoton production vertex is important for the measurement of $m_{\gamma\gamma}$. Diphoton primary vertex used in analysis is selected by using a neural-network algorithm based on primary vertex and track information among all reconstructed vertices. The direction information of the two photons measured in the inner detector and calorimeters are also used [1]. For simulated gluon-gluon fusion events, the efficiency of selecting a diphoton vertex within 0.3 mm of the true $H \rightarrow \gamma\gamma$ production vertex is 79% by using this neural-network algorithm. This fraction ranges from 84% to 97% for the other Higgs production modes, increasing with the presence of charged leptons or jet activities. $Z \rightarrow e^+e^-$ events in data and simulation are used to validate the performance of the diphoton primary vertex neural-network algorithm, by treating the electron candidates as photon candidates, with the tracks associated with them ignored. Sufficient agreement between the data and the simulation is found. The direction of the photon candidates are redefined by the diphoton primary vertex, giving an improved diphoton invariant mass resolution. The invariant mass of the two photons is given by $m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\alpha)}$, where E_1 and E_2 refer to the energies of the leading/subleading photons and α is the opening angle of the two photons with respect to the diphoton production vertex selected.

CHAPTER 4

Measurement of $H \rightarrow \gamma\gamma$ cross section and couplings

4.1 Introduction

The Higgs boson decay into two photons ($H \rightarrow \gamma\gamma$) is an important channel to study the properties of the Higgs boson and to probe the Standard Model. Thanks to the high efficiency of photon reconstruction and identification (Section 3.2.1), although the branching ratio, $(2.27 \pm 0.07) \times 10^{-3}$ for $m_h = 125.09$ GeV [3] is small, a reasonably large signal yields can be obtained. Due to the excellent photon energy resolution of the ATLAS calorimeter, the signal appears as a narrow peak on a falling background in the diphoton invariant mass ($m_{\gamma\gamma}$) spectrum. Thus the Higgs boson signal can be extracted using an appropriate fit to the whole spectrum. All the measurements are performed under the assumption that the Higgs boson mass is 125.09 GeV corresponding to the central value of the combination of ATLAS and CMS measurements in Run 1 [39], and are compared to Standard Model predictions.

This chapter is structured as follows: Section 4.2 introduces the major background processes in diphoton final state at the LHC and Section 4.3 describes the data and simulation samples. An overview of the event selection and categorization is given in Section 4.4. The data-MC comparison in reconstructed categories are shown in Section 4.5. Section 4.6 provides explanation of the signal and background modeling used in the measurement and Section 4.7 provides a short description of the statistical procedures. The details of the sources of systematic uncertainties are summarized in Section 4.8. Section 4.9 presents results including the measurements of the total Higgs boson production-mode cross sections and “signal strengths”, cross sections of the main production modes of the Higgs boson, and the cross sections using the SM production modes as “templates” in simplified regions. Finally, Section 4.10 gives the conclusion.

In this chapter, cross sections times branching ratio of the Higgs to two photons $B(H \rightarrow \gamma\gamma)$ are measured for inclusive Higgs boson production, as well as for the main production modes of the Higgs boson (Section 1.2), including gluon–gluon fusion (ggF), vector-boson fusion (VBF), Higgs boson production in association with a vector boson (VH), and production of a Higgs boson in association with a top–antitop quark pair ($t\bar{t}H$) or a single top quark (tHq and tHW).

In order to maximize the sensitivity to different production modes and the different regions of the simplified template cross sections (Section 1.3), multiple categories are developed based on the reconstructed event properties, each of which is particularly sensitive to a specific process or event topology.

The signal strength μ , defined as the ratio of an observed yield to its SM expectation (Equation 4.1), is reported inclusively as well as for the different production processes μ_i . It is thus a hint of potential deviations from the SM. For a specific production mode i and decay final state f , the signal yield is expressed in terms of a single modifier μ_{if} , as the production cross section σ_i and the branching fraction B_f cannot be separately measured without further assumptions. The SM expectation by definition is $\mu_{if} = 1$.

$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \times \frac{B_f}{B_f^{\text{SM}}}. \quad (4.1)$$

To disentangle the production mode from decay, ratios of the different production-mode cross sections with respect to gluon-gluon fusion are also reported. Finally, to probe the Higgs boson couplings to the different particles at tree-level, coupling-strength modifiers (Section 1.4), which are scale factors related to the amplitude of Higgs boson couplings to various particles, are also reported.

4.2 Background processes in diphoton final state at the LHC

At the Large Hadron Collider, the cross section of $pp \rightarrow H \rightarrow \gamma\gamma$ is much smaller than the one of continuum background processes. These mainly arise from prompt $\gamma\gamma$ production, single-photon production with an additional jet in the event misidentified as a photon, and di-jet production with two jets misidentified as photons. The distribution of $m_{\gamma\gamma}$ is used as the final discriminant variable in order to separate the Higgs boson events from the background.

Two prompt photons from the Standard Model processes in Figure 4.1 are considered “irreducible background” in the diphoton analysis. It is the largest contribution to the background, taking around 79% of the inclusive diphoton events after the selection.

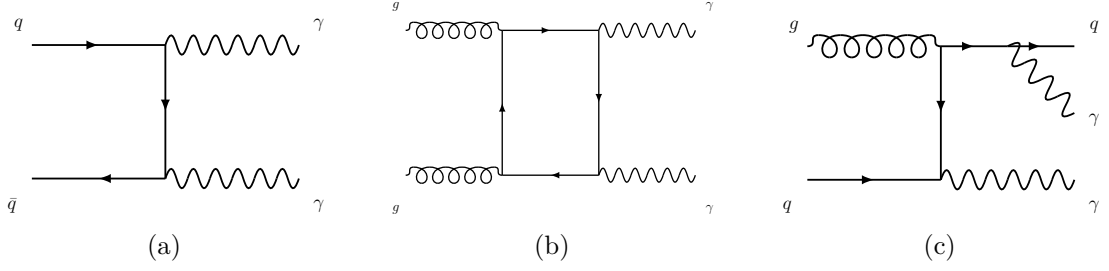


Fig. 4.1: Feynman diagrams at leading-order of non-resonant Standard Model diphoton production via (a) $q\bar{q} \rightarrow \gamma\gamma$, (b) $gg \rightarrow \gamma\gamma$, and (c) Bremsstrahlung $gq \rightarrow q\gamma\gamma$.

The single-photon production where an additional jet (γj) in the event is misidentified as a photon is the second largest contribution to the background processes, which is shown in Figure 4.2. The di-jet ($j j$) process can contribute up to a few percent depending on the event and object selection criteria. Drell-Yan events where both electrons are misidentified as photons also contribute a small fraction ($< 1\%$) to the total background. After applying the photon quality requirement (Section 3.2.1), around 21% of the inclusive diphoton events are from those processes with a photon, which is considered as the “reducible background”.

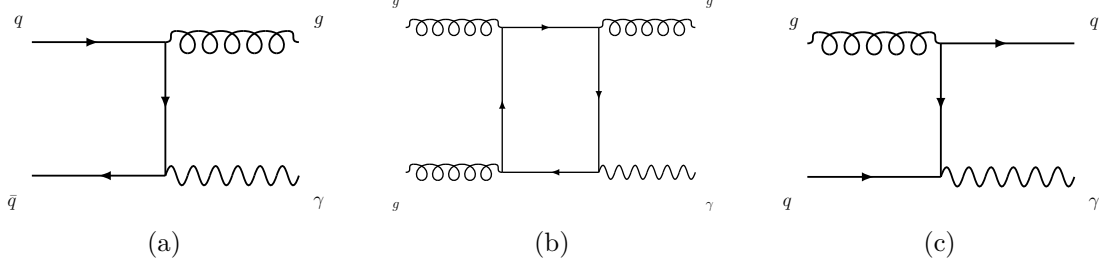


Fig. 4.2: Feynman diagrams at leading-order of non-resonant Standard Model $\gamma+j$ production via (a) $q\bar{q} \rightarrow \gamma j$, (b) $gg \rightarrow \gamma j$, and (c) $gq \rightarrow \gamma j$.

The data-driven background method is widely used in diphoton analysis, by which background is estimated from parameterizing the data sideband and then interpolating into the signal region, but not directly use theoretical predictions of background processes. The theoretical knowledge is used to validate the data-driven background estimation, which will be discussed later in Section 4.6.

4.3 Data and Monte Carlo samples

The dataset used in this analysis corresponds to an integrated luminosity of 36.1 fb^{-1} with a common uncertainty of 3.2%. 3.2 fb^{-1} were taken in 2015 and 32.9 fb^{-1} were collected in 2016.

The simulated signal sample used in this analysis is summarized in Table 4.1.

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s} = 13$ TeV	Order of calculation of σ
ggH	Powheg NNLOPS	Pythia8	PDF4LHC15	48.52	N ³ LO(QCD)+NLO(EW)
$qq' \rightarrow qq'H$	Powheg-Box	Pythia8	PDF4LHC15	3.78	NNLO(QCD)+NLO(EW)
WH	Powheg-Box	Pythia8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$qqZH$	Powheg-Box	Pythia8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$ggZH$	Powheg-Box	Pythia8	PDF4LHC15	0.12	NLO+NLL(QCD)
$q\bar{q}/gg \rightarrow t\bar{t}H$	MG5_aMC@NLO	Pythia8	NNPDF3.0	0.51	NLO(QCD)+NLO(EW)
$b\bar{b}H$	MG5_aMC@NLO	Pythia8	CT10	0.49	5FS(NNLO)+4FS(NLO)
t -channel tH	MG5_aMC@NLO	Pythia8	CT10	0.07	4FS(LO)
W -associated tH	MG5_aMC@NLO	Herwig++	CT10	0.02	5FS(NLO)

Table. 4.1: Summary of the event generators and PDF sets used to model the signal processes. The SM cross sections σ at $\sqrt{s} = 13$ TeV correspond to $m_h = 125.09$ GeV. The perturbation orders of each calculation is also given.

Signal samples are produced at a mass of $m_h = 125$ GeV, $\Gamma_H = 4.07$ MeV [2], and a shift of 0.09 GeV is applied on the mean parameter of the signal shape function. Samples are normalized by the latest available theoretical calculations of the corresponding SM production cross sections [3]. The normalization of all Higgs boson samples also accounts for the $H \rightarrow \gamma\gamma$ branching ratio of 0.227% calculated with PROPHECY4F [40, 41, 42] and HDECAY [43, 44].

The ggF events are generated at next-to-next-to-leading-order (NNLO) accuracy in QCD using the Powheg NNLOPS program [45] passed to Pythia8 [46] to provide parton showering, hadronization and underlying event, and with AZNLO [47] tune. Next-to-leading order (NLO) EW corrections are also applied [48, 49]. NLO electroweak corrections are also applied to the sample normalization [50, 51, 49, 52].

The VBF events are generated at NLO accuracy in QCD using the Powheg-Box program [53, 54, 55, 56] with the PDF4LHC15 PDF set, interfaced with Pythia8 normalized to a cross section calculated with full NLO QCD and EW corrections [57, 58, 59] with an approximate NNLO QCD correction applied [57, 58, 60].

The associated production events from WH and ZH are fully generated at NLO accuracy in QCD through qq/qg -initiated production and $gg \rightarrow ZH$ production using Powheg-Box [61] with the PDF4LHC15 PDF set. Pythia8 with the AZNLO parameter set is used for parton showering, hadronization and the underlying event. The $q\bar{q}' \rightarrow VH$ predictions are normalized to cross sections calculated at NLO [62] and at NNLO [63] with NLO EW radiative corrections [64] applied, and next-to-leading-logarithm accuracy is applied in QCD for $gg \rightarrow ZH$ [63, 65, 66].

The associated production events from $t\bar{t}H$ are generated at NLO accuracy in

QCD using MG5_aMC@NLO [67] with the NNPDF3.0 PDF set [68], and showered with Pythia8. For the $t\bar{t}H$ normalization, full NLO QCD and NLO electroweak corrections have been calculated [69, 70, 71, 72].

Other rare production contributions are considered. $b\bar{b}H$ is simulated using MG5_aMC@NLO [73] interfaced to Pythia8 with the CT10 PDF set [74]. tHW and tHq are generated at NLO accuracy by using MG5_aMC@NLO interfaced to Herwig++ [75, 76, 77].

The irreducible $\gamma\gamma$ and $V\gamma\gamma$ background samples are simulated by producing with two direct photons plus 0, 1, 2 or 3 jets. The samples are generated using Sherpa event generator [78] with CT10 tuning, slicing by $m_{\gamma\gamma}$. The fast simulation is used to produce the very large $\gamma\gamma$ background samples.

The generated events are processed through a Geant4 [25] simulation of the ATLAS detector [23], and then treated similarly as data by using analysis software for reconstruction.

4.4 Event selection and categorization

4.4.1 Event selection

With the primary photon objects reconstruction (Section 3.2.1), multiple selections are applied to select events for analysis.

At first, events are preselected by applying the HLT_g35_loose_g25_loose diphoton trigger (triggered by two clusters in the EM calorimeter. The transverse energy should be above 35 GeV and 25 GeV for the leading and subleading cluster, respectively), requiring the shape of the energy deposition loosely consistent with that expected from an electromagnetic shower initiated by a photon [27] with $|\eta| < 2.37$ (excluding the crack region between the barrel and endcap calorimeters of $1.37 < |\eta| < 1.52$). Only events in which all the sub-detectors are fully operational are kept.

Then the diphoton candidate is constructed by two photon candidates with the highest E_T , to define the diphoton primary vertex.

Following the identification of the diphoton primary vertex, the leading (sub-leading) photons must fulfill the kinematics requirement: $E_T/m_{\gamma\gamma} > 0.35$ (0.25), fulfill the tight identification criteria, meet the calorimeter and track isolation requirements.

Then a mass window cut is applied, to select diphoton candidates with invariant mass $m_{\gamma\gamma}$ between 105 GeV and 160 GeV.

Events that satisfy the inclusive diphoton selection are then classified into 31 exclusive categories that are optimized for the production mode cross section and

stage-1 simplified template cross section measurements.

The categories are defined using the expected properties of the different production mechanisms. The definition of each category was optimized using simulated events. The rarest processes with a smaller cross section has priority in the sequence of the classification. In order to reduce as much as possible the rate of contamination among reconstructed categories, the ordering is chosen to give preference to categories targeting the rarest Higgs production modes as shown in Figure 4.3. Only events fail the prior category selections can be tested with the next categorization selections.

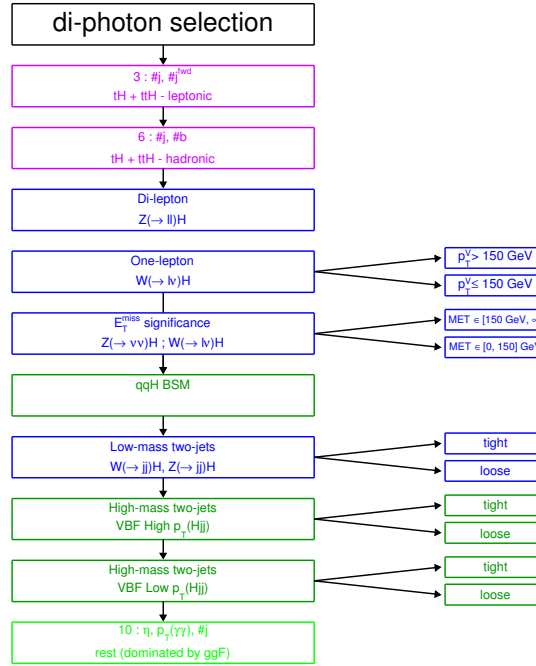


Fig. 4.3: Flow-chart of the event categorization, including 9 $t\bar{t}H$ and tH enriched categories (3 leptonic and 6 hadronic), 5 VH leptonic enriched categories, 3 BSM enriched and VH hadronic categories, 4 VBF enriched categories and 10 Untagged(ggF) categories, giving the order of selection of the different categories and the targeted production process.

The signal significance (Equation 4.2) and the availability of data statistics are both considered in developing categorizations. The selection criteria are described in more detail following the same ordering in the following subsections.

$$Z = \sqrt{2(S + B) \ln \left(1 + \frac{S}{B} \right) - 2S} \quad (4.2)$$

where S is the signal yields from simulated samples, and B is the background yields, estimated either from simulation or data-driven backgrounds.

4.4.2 $t\bar{t}H$ and tH enriched categories

Though still rare, the $t\bar{t}H$ production mode has a great advantage in Run 2 as the cross section increases by a factor of 3.9 with respect to the Run 1, nearly double that of other Higgs productions. The $t\bar{t}H$ production mode has a signature dominated by the top quark pair; featuring many jets, b-jets, and up to two charged leptons.

Nine categories are developed for selecting events produced in association with a top quark through the $t\bar{t}H$, tHq , and tHW production modes. Both the hadronic and leptonic decaying top quarks are considered. Events are splitted into hadronic categories, where top quarks in the event decay to hadrons via $t \rightarrow Wb \rightarrow qq'b$; and leptonic categories, where at least one top quark decays to a charged lepton via $t \rightarrow Wb \rightarrow \ell\nu b$. The SM tH production are probed by the single top quark categories.

Three categories target the leptonic channel by requiring the presence of at least one b -tagged jet with transverse momentum greater than 25 GeV and at least one prompt lepton.

Six categories target the hadronic decay channel by selecting events with at least three jets, of which at least one is b -tagged, and no prompt leptons. A boosted decision tree (BDT) is trained to improve $t\bar{t}H$ signal signal significance.

Table 4.2 summarizes the selections in $t\bar{t}H$ and tH categories.

Category	Selection
Leptonic	
tHlep, 0fwd	$N_{lep} = 1, N_{jets}^{cen} \leq 3, N_{tags}^{70} \geq 1, N_{jets}^{fwd} = 0 (p_T^{jet} > 25 \text{ GeV})$
tHlep, 1fwd	$N_{lep} = 1, N_{jets}^{cen} \leq 4, N_{tags}^{70} \geq 1, N_{jets}^{fwd} \geq 1 (p_T^{jet} > 25 \text{ GeV})$
ttHlep	$N_{lep} \geq 1, N_{jets}^{cen} \geq 2, N_{tags}^{70} \geq 1, Z_{\ell\ell} \text{ veto } (p_T^{jet} > 25 \text{ GeV})$
Hadronic	
ttH had BDT1	$N_{lep} = 0, N_{jets} \geq 3, N_{tags}^{70} \geq 1, \text{BDT} > 0.92$
ttH had BDT2	$N_{lep} = 0, N_{jets} \geq 3, N_{tags}^{70} \geq 1, 0.83 < \text{BDT} < 0.92$
ttH had BDT3	$N_{lep} = 0, N_{jets} \geq 3, N_{tags}^{70} \geq 1, 0.79 < \text{BDT} < 0.83$
ttH had BDT4	$N_{lep} = 0, N_{jets} \geq 3, N_{tags}^{70} \geq 1, 0.52 < \text{BDT} < 0.79$
tH had 4j1b	$N_{lep} = 0, N_{jets}^{cen} = 4, N_{tags}^{70} = 1, \text{BDT} < 0.52$
tH had 4j2b	$N_{lep} = 0, N_{jets}^{cen} = 4, N_{tags}^{70} \geq 2, \text{BDT} < 0.52$

Table. 4.2: Event selections for the $t\bar{t}H$ and tH categories with events prioritized in descending order. Events are separated into a leptonic and hadronic channels based on the number of leptons in each event (N_{lep}).

The distributions of two of the discriminating variables are shown in Figure 4.4.

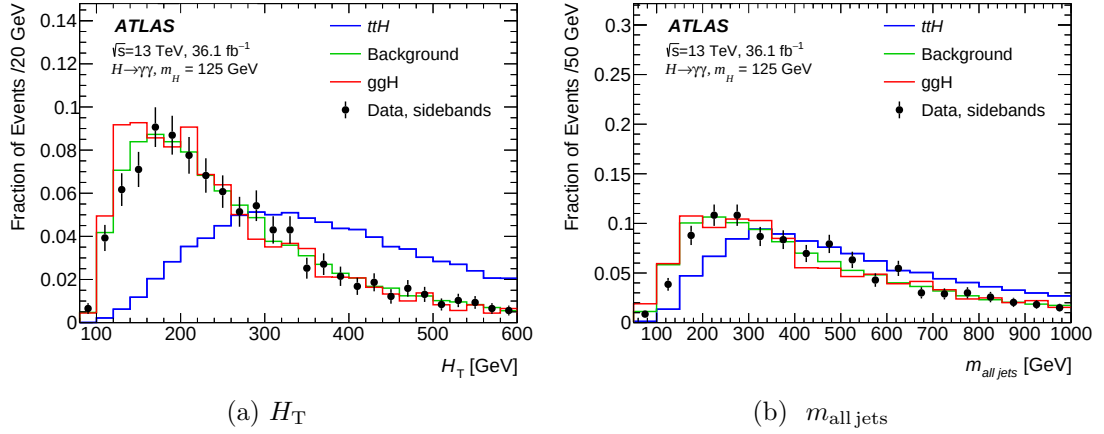


Fig. 4.4: Normalized distributions for the expected signal, background and the data in the control region of two kinematic variables used in the hadronic $t\bar{t}H$ categories' selections.

4.4.3 VH non-hadronic categories

The VH non-hadronic categories probe WH and ZH production. It can be separated into various decay modes: $W(l\nu)H$, characterised with the presence of a single charged lepton and missing transverse energy (E_T^{miss}); $Z(l\bar{l})H$, characterised by the presence of two charged, same-flavor leptons whose invariant mass peaks at the mass of the Z ; and $Z(\nu\nu)H$, characterised by the absence of charged leptons and presence of E_T^{miss} .

4.4.3.1 VH dilepton category

The purpose of this category is to isolate the ZH production mode tagging the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decays.

From the formalism of STXS Stage 1, there are four signal processes relevant to the VH dilepton category : ZH with $p_T^V < 150$ GeV, $150 < p_T^V < 250$ GeV with 0j, $150 < p_T^V < 250$ GeV with 1j, and $p_T^V > 250$ GeV. The other contributions are considered as background processes:

$$\begin{aligned} S &= n_{ZH \text{ truth signal}} \\ B &= n_{\text{QCD}} + n_{V\gamma(\gamma)} + n_{\text{Higgs background}}, \end{aligned} \quad (4.3)$$

where n_{QCD} refers to $\gamma\gamma$, γj and $j j$ QCD backgrounds.

The optimization of this category's significance is done before the end of 2016 data-taking, by which a 35 fb $^{-1}$ total integrated luminosity is expected in the end of 2016, thus all MC samples are normalized to an integrated luminosity of 35 fb $^{-1}$. This category requires at least two same-flavor, opposite-sign leptons whose invariant mass is in the range $70 < m_{ll} < 110$ GeV. The corresponding

reconstructed m_{ll} and p_{Tll} ($= p_T^V$) distributions are shown in Figure 4.5. Each truth process can be well separated using the p_{Tll} variable.

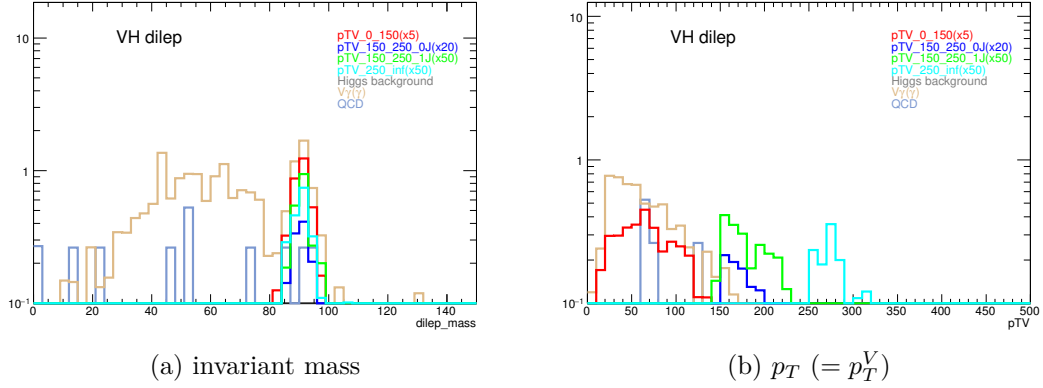


Fig. 4.5: Kinematic variable distributions of the dilepton system among various processes. Events are required to have at least two leptons.

To optimize on a sufficient number of events, data corresponding to 30.2 fb^{-1} (which is collected by the time developing this category) in the $m_{\gamma\gamma}$ sideband that excludes the signal mass range $[120-130] \text{ GeV}$ is used to make the decision of splitting STXS categories. The events passing the VH dilepton selection are split into two categories: $p_{Tll} < 150 \text{ GeV}$ and $p_{Tll} > 150 \text{ GeV}$. Due to the limited number of data events in the sideband, there is no splitting by jet multiplicity, and the bins with $p_{Tll} > 150 \text{ GeV}$ are merged together. The cutflow table for this category is presented in Table 4.3.

120 – 130 GeV	background	$p_{TV} < 150$	Z	$150 < p_{TV} < 250, 0J$	Z	$150 < p_{TV} < 250, 1J$	Z	$p_{TV} > 250$	Z
all dilepton events	5.278	0.749	0.319	0.067	0.029	0.050	0.022	0.052	0.023
$70 < m_{ll} < 110 \text{ GeV}$	1.654	0.701	0.512	0.063	0.049	0.045	0.035	0.043	0.033
$p_{Tll} < 150 \text{ GeV}$	1.453	0.700	0.541	0.002		0.003		0.000	
$p_{Tll} > 150 \text{ GeV}$	0.201	0.001		0.061	0.129	0.043	0.092	0.043	0.092

Table. 4.3: Cutflow of the events in VH -dilepton categories.

After optimization there are roughly 5 events of data in the sideband (which excludes the signal mass range $[120-130] \text{ GeV}$) remaining in the $p_{Tll} < 150 \text{ GeV}$ category and < 5 events left in the $p_{Tll} > 150 \text{ GeV}$ category. Because it is not practical to fit the shape and normalization with only a handful of data points, the two dilepton categories are merged to form a single category with roughly 10 events in the data sideband.

4.4.3.2 VH one-lepton category

The one-lepton category is defined by selecting events in the inclusive sample that contain exactly one candidate electron or muon in order to select $WH \rightarrow \ell \nu \gamma \gamma$ events. This category provides a clean topology for separating the associated production modes of W leptonic decays, but still contains ZH and $t\bar{t}H$ events.

From the formalism of STXS in its stage 1, there are four signal processes relevant to this VH one-lepton category (Table 4.16): WH with $p_T^V < 150$ GeV, $150 < p_T^V < 250$ GeV with $0j$, $150 < p_T^V < 250$ GeV with $1j$, and $p_T^V > 250$ GeV. The other contributions are considered background processes:

$$\begin{aligned} S &= n_{WH \text{ signal}} \\ B &= n_{\text{QCD}} + n_{V\gamma(\gamma)} + n_{\text{Higgs background}}, \end{aligned} \quad (4.4)$$

where n_{QCD} refers to $\gamma\gamma$, γj and jj . The optimization of this category is performed by normalizing all MC samples to an integrated luminosity of 35 fb^{-1} . The signal significance used to optimize this category is defined by Equation 4.2.

This category requires one lepton satisfying the selection criteria. To reject events with one fake photon and one electron coming from a Z boson, a $m_{e\gamma}$ in $[84, 94]$ GeV veto for any photon-electron pair is applied.

The distribution of the discriminant variable p_T^{l+MET} is shown in Figure 4.6.

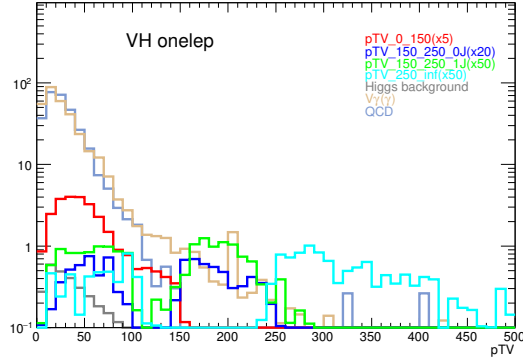


Fig. 4.6: Distribution of p_T of lepton + E_T^{miss} among various processes. Events are required to have exactly one lepton.

Since the targeting processes contain a neutrino in the final state, the E_T^{miss} -related variable E_T^{miss} significance should be taken into account to improve the significance. This variable is defined as

$$E_T^{\text{miss}} \text{ significance} = \frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}, \quad (4.5)$$

where $\sum E_T$ is the scalar sum of the transverse energies of all objects. The E_T^{miss} and $\sum E_T$ are measured in GeV. The distribution of the E_T^{miss} significance and the significance scan results are shown in Figure 4.7. It can help to improve the signal significance to cut on E_T^{miss} significance > 1 in the $p_T^V < 150$ GeV category.

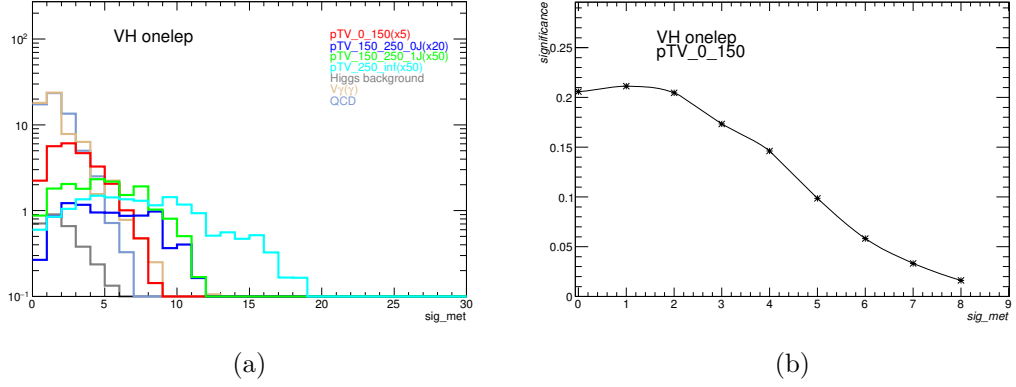


Fig. 4.7: (a) Distribution of E_T^{miss} significance (b) Significance scan at the different cut value of E_T^{miss} significance.

The cutflow of this category is shown in Table 4.4.

120 – 130 GeV	background	$p_{TV} < 150$	Z	$150 < p_{TV} < 250, 0j$	Z	$150 < p_{TV} < 250, 1j$	Z	$p_{TV} > 250$	Z
1 lepton, pass $m_{e\gamma}$ veto	127.8	5.134	0.451	0.458	0.041	0.341	0.030	0.341	0.030

Table. 4.4: Cutflow of events in VH -lepton categories.

4.4.3.3 VH MET category

A Higgs produced in association with Z may produce significant missing energy. The selected diphoton candidates that are not classified in the lepton category may pass the MET category requirements, and it is dominated by the events from ZH process.

From the formalism of STXS in its stage 1, there are four signal processes relevant to this VH MET category (Table 4.16), which are ZH with $p_T^V < 150$ GeV, $150 < p_T^V < 250$ GeV with $0j$, $150 < p_T^V < 250$ GeV with $1j$ and $p_T^V > 250$ GeV. The other contributions are considered as background processes:

$$\begin{aligned}
 S &= n_{ZH \text{ signal}} \\
 B &= n_{\text{QCD}} + n_{V\gamma(\gamma)} + n_{\text{Higgs background}},
 \end{aligned}
 \tag{4.6}$$

where n_{QCD} refers to $\gamma\gamma$, γj and jj . The signal significance of this category is defined as Formula 4.2.

Each truth category can be reasonably well distinguished using reconstructed E_T^{miss} (TST). The events passing the VH -MET categories are split into three categories: $E_T^{\text{miss}} < 150$ GeV, $150 < E_T^{\text{miss}} < 250$ GeV, and $E_T^{\text{miss}} > 250$ GeV. Due to the limited number of data events in the sideband, there is no splitting in jet multiplicity. The distribution of the E_T^{miss} discriminant variable and the significance scan are shown in Figure 4.8. Thus, to maximize the significance, a

$E_T^{\text{miss}} > 80$ GeV cut is applied to the category targeting $p_T^V < 150$ GeV truth events.

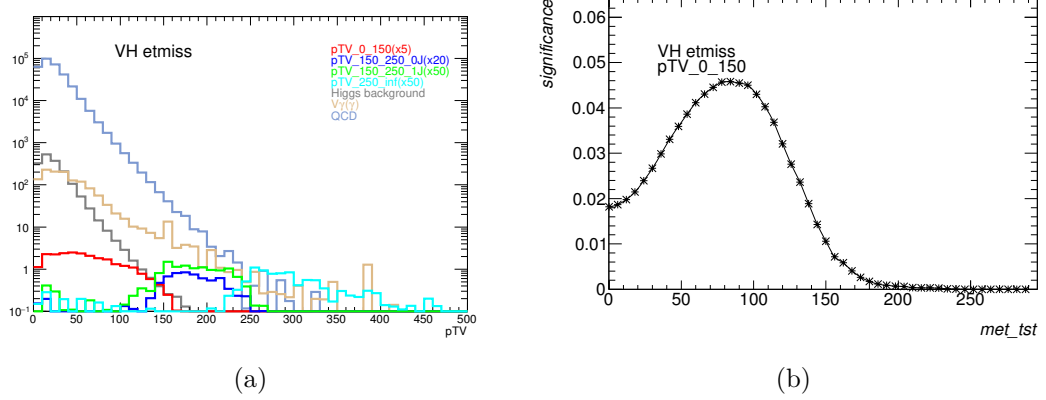


Fig. 4.8: (a) Distribution of E_T^{miss} for various processes. (b) significance scan to determine the low-edge cut on E_T^{miss} .

The significance is further improved using a cut on the E_T^{miss} significance defined in Equation 4.5. Here, the E_T^{miss} significance is scanned to find the optimal value. The distribution of this variable and the scan results are shown in Figure 4.9. The optimization is performed by normalizing all MC samples to an integrated luminosity of 35 fb^{-1} , which is the expected integrated luminosity in the end of 2016 by the time developing this category.

It is important to note that E_T^{miss} has complications in diphoton events due to the primary vertex dependence. The current Run 2 E_T^{miss} reconstruction strategy used here is TST. However, when the hardest final state particles are photons without tracks, the soft term is more likely to be reconstructed with respect to the wrong vertex.

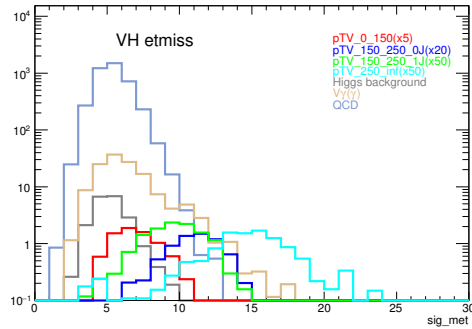


Fig. 4.9: Distribution of E_T^{miss} significance in various processes. The events in this figure are with $E_T^{\text{miss}} > 80$ GeV cut.

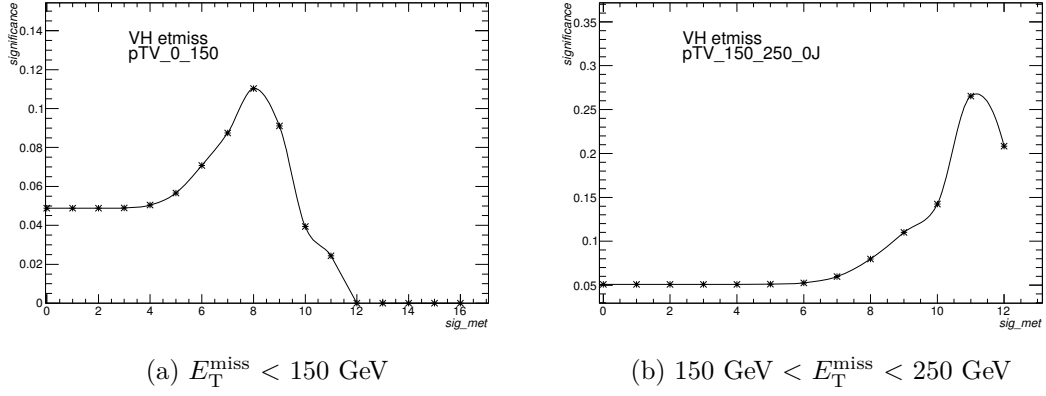


Fig. 4.10: Significance scan of the low edge cut on E_T^{miss} significance for different categories.

From the scan results and the statistic of data in sideband which exclude the signal mass range [120-130] GeV, considering the implementation of the following statistical procedure, E_T^{miss} significance > 8 is applied to $p_T^V < 150$ GeV truth bin, and E_T^{miss} significance > 9 is applied to $150 < p_T^V < 250$ GeV truth bin.

To keep an adequate number of events, data corresponding to 30.2 fb^{-1} in the sideband is used to make the decision of splitting the STXS categories. The cutflow of the VH MET categories is in Table 4.5.

120 – 130 GeV	background	$p_{TV} < 150$	Z	$150 < p_{TV} < 250, 0J$	Z	$150 < p_{TV} < 250, 1J$	Z	$p_{TV} > 250$	Z
diphoton events remaining	66050	4.725	0.018	0.378	0.001	0.267	0.001	0.256	0.001
$E_T^{\text{miss}} > 250$ GeV	2.315	0.000		0.012		0.008		0.195	0.127

Table. 4.5: Cutflow of events in VH MET categories.

There are roughly 20 data sideband events in the $E_T^{\text{miss}} < 150$ GeV category, around 20 in the $150 < E_T^{\text{miss}} < 250$ GeV category, and around 10 in the $E_T^{\text{miss}} > 250$ GeV category. Due to issues with MC statistics and background modeling, the $150 < E_T^{\text{miss}} < 250$ GeV and $E_T^{\text{miss}} > 250$ GeV categories are merged into a single category.

4.4.4 BSM enriched and VH hadronic categories

According to Simplified Template Cross Section, the VH process with a hadronically decaying vector boson is considered to be part of what is called “VBF production”, which is defined as electroweak qqH production. A “jet BSM” category is defined to provide sensitivity to potential beyond SM contributions. Events with a leading jet with transverse momentum greater than 200 GeV are selected into this category.

Two VH hadronic categories target VH production with a hadronically decaying vector boson with at least two jets in events. A BDT classifier is built based on several kinematic information. Two categories (“ VH had loose” and “ VH had tight”) are defined by using the BDT response as a discriminating variable, with an expected fraction of signal events due to VH production of 25% and 42%, respectively.

Figure 4.11 shows the distributions of m_{jj} and $p_{Tt}^{\gamma\gamma}$, which are used as two of the discriminant variables in the BDT.

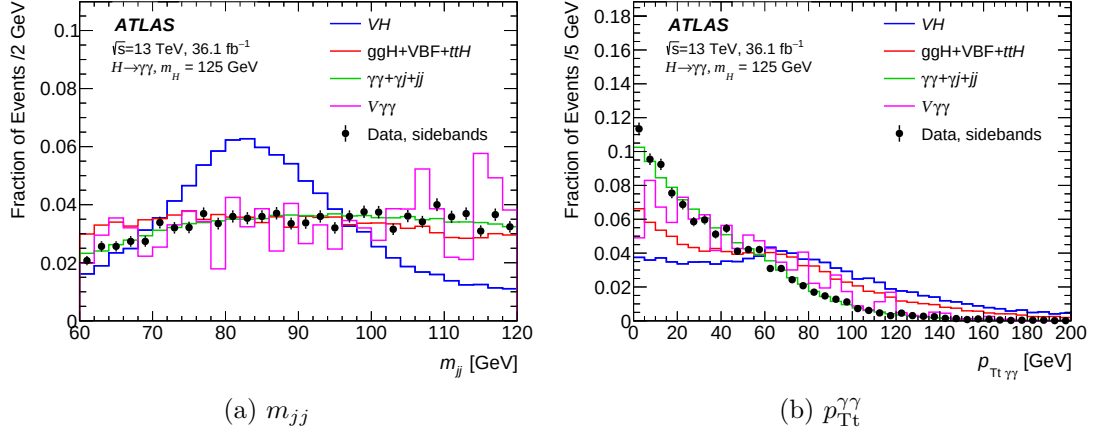


Fig. 4.11: Normalized distributions for the expected signal, background and the data in the control region of two kinematic variables used for the VH hadronic categories' selections.

4.4.5 VBF enriched categories

Vector boson fusion is the second-most prominent Higgs production process. It has leading role in determining the Higgs coupling to gauge bosons. Four categories are developed to enhance the sensitivity to vector boson fusion production. At least two hadronic jets are required, and the selections applied are based on the two leading jets (j_1, j_2) in the event.

Firstly two regions are used to split events based on the value of the transverse momentum p_T^{Hjj} of the vector sum of the momenta of the reconstructed Higgs boson and of the two leading jets. Then a BDT based on different kinematic variables is used to classify events in each region.

Four exclusive categories are defined with “loose” and “tight” requirements on the BDT classifier in the two p_T^{Hjj} regions.

In the $p_T^{Hjj} > 25$ GeV region, the fraction of VBF events among all Higgs boson events for “tight” category “loose” categories are expected to be 49% and 20%, respectively. In the $p_T^{Hjj} < 25$ GeV region, the same fraction number for

“tight” and “loose” categories are expected to be 85% and 61%.

Figure 4.12 shows the distributions of two discriminant variables $|\Delta\eta_{jj}|$ and $|\Delta\phi_{\gamma\gamma,jj}|$. Both of the variables give a good separation power between VBF events and events from non-VBF processes.

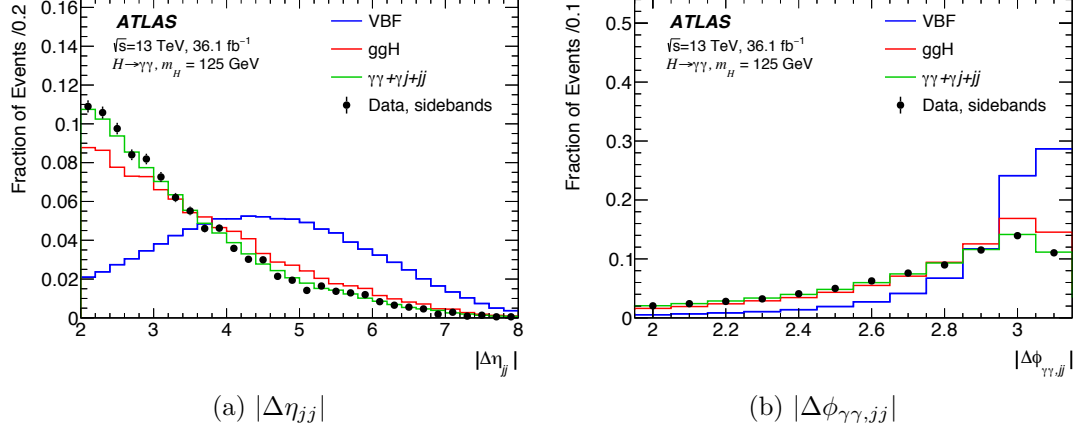


Fig. 4.12: Normalized distributions for the expected signal, background and the data in the control region of two kinematic variables used for the VBF categories' selections.

4.4.6 Untagged categories

The remaining events (mainly from ggF production) are separated into events with zero jet, exactly one-jet, or at least two jets. The zero-jet events are split into a “ggF 0J Cen” category where both photons are with $|\eta| < 0.95$, and a “ggF 0J Fwd” category where at least one photon with $|\eta| \geq 0.95$. The exclusive one-jet (“ggF 1J”) and inclusive two-jet (“ggF 2J”) events are further split into regions of diphoton transverse momentum: $p_T^{\gamma\gamma} \in [0, 60)$ (“Low”), $[60, 120)$ (“Med”), $[120, 200)$ (“High”) or > 200 GeV (“BSM”), the latter of which is particularly sensitive to the presence of BSM physics in the loop diagrams associated with the gluon–gluon fusion production mode.

4.4.7 Categorization summary

Table 4.6 shows the selection requirements of each category. The predicted signal efficiencies times acceptance and the event fractions per production mode for each category are given in Table 4.7.

Figure 4.13 shows the fractions of the STXS truth signal events in each reconstructed category.

Finally, the fractions of truth signal events from production mode, in each category are shown in Figure 4.14.

Category	Selection
tH lep 0fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 3, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} = 0 (p_{\text{T}}^{\text{jet}} > 25 \text{ GeV})$
tH lep 1fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 4, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} \geq 1 (p_{\text{T}}^{\text{jet}} > 25 \text{ GeV})$
ttH lep	$N_{\text{lep}} \geq 1, N_{\text{jets}}^{\text{cen}} \geq 2, N_{b\text{-tag}} \geq 1, Z_{\ell\ell} \text{ veto } (p_{\text{T}}^{\text{jet}} > 25 \text{ GeV})$
ttH had BDT1	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, \text{BDT}_{\text{ttH}} > 0.92$
ttH had BDT2	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.83 < \text{BDT}_{\text{ttH}} < 0.92$
ttH had BDT3	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.79 < \text{BDT}_{\text{ttH}} < 0.83$
ttH had BDT4	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.52 < \text{BDT}_{\text{ttH}} < 0.79$
tH had 4j1b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} = 1 (p_{\text{T}}^{\text{jet}} > 25 \text{ GeV})$
tH had 4j2b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} \geq 2 (p_{\text{T}}^{\text{jet}} > 25 \text{ GeV})$
VH dilep	$N_{\text{lep}} \geq 2, 70 \text{ GeV} \leq m_{\ell\ell} \leq 110 \text{ GeV}$
VH lep High	$N_{\text{lep}} = 1, m_{e\gamma} - 89 \text{ GeV} > 5 \text{ GeV}, p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} > 150 \text{ GeV}$
VH lep Low	$N_{\text{lep}} = 1, m_{e\gamma} - 89 \text{ GeV} > 5 \text{ GeV}, p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150 \text{ GeV}, E_{\text{T}}^{\text{miss}} \text{ significance} > 1$
VH MET High	$150 \text{ GeV} < E_{\text{T}}^{\text{miss}} < 250 \text{ GeV}, E_{\text{T}}^{\text{miss}} \text{ significance} > 9 \text{ or } E_{\text{T}}^{\text{miss}} > 250 \text{ GeV}$
VH MET Low	$80 \text{ GeV} < E_{\text{T}}^{\text{miss}} < 150 \text{ GeV}, E_{\text{T}}^{\text{miss}} \text{ significance} > 8$
jet BSM	$p_{\text{T,j1}} > 200 \text{ GeV}$
VH had tight	$60 \text{ GeV} < m_{\text{jj}} < 120 \text{ GeV}, \text{BDT}_{\text{VH}} > 0.78$
VH had loose	$60 \text{ GeV} < m_{\text{jj}} < 120 \text{ GeV}, 0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF tight, high p_{T}^{Hjj}	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_{\text{T}}^{Hjj} > 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.47$
VBF loose, high p_{T}^{Hjj}	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_{\text{T}}^{Hjj} > 25 \text{ GeV}, -0.32 < \text{BDT}_{\text{VBF}} < 0.47$
VBF tight, low p_{T}^{Hjj}	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_{\text{T}}^{Hjj} < 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.87$
VBF loose, low p_{T}^{Hjj}	$ \Delta\eta_{jj} > 2, \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2}) < 5, p_{\text{T}}^{Hjj} < 25 \text{ GeV}, 0.26 < \text{BDT}_{\text{VBF}} < 0.87$
ggH 2J BSM	$\geq 2 \text{ jets}, p_{\text{T}}^{\gamma\gamma} \geq 200 \text{ GeV}$
ggH 2J High	$\geq 2 \text{ jets}, p_{\text{T}}^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggH 2J Med	$\geq 2 \text{ jets}, p_{\text{T}}^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggH 2J Low	$\geq 2 \text{ jets}, p_{\text{T}}^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggH 1J BSM	$= 1 \text{ jet}, p_{\text{T}}^{\gamma\gamma} \geq 200 \text{ GeV}$
ggH 1J High	$= 1 \text{ jet}, p_{\text{T}}^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggH 1J Med	$= 1 \text{ jet}, p_{\text{T}}^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggH 1J Low	$= 1 \text{ jet}, p_{\text{T}}^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggH 0J Fwd	$= 0 \text{ jets}, \text{one photon with } \eta > 0.95$
ggH 0J Cen	$= 0 \text{ jets}, \text{two photons with } \eta \leq 0.95$

Table. 4.6: Shorthand label and event selection defining each of the 31 event reconstruction categories for the measurement of the signal strengths and simplified template cross sections. The labels denote the predominant production process or kinematic properties the category targets.

Category	ggF		VBF		WH		ZH		ttH		bbH		tHq		tHW		All
	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	ϵ [%]	f [%]	N_S
ggH 0J Cen	8.9	97.3	1.2	1.1	1.4	0.4	1.9	0.4	nil	nil	8.2	0.9	nil	nil	nil	nil	333.5
ggH 0J Fwd	15.5	97.0	2.4	1.2	3.0	0.5	3.7	0.4	nil	nil	14.7	0.9	0.2	nil	0.1	nil	579.5
ggH 1J Low	7.2	90.5	5.7	5.7	5.0	1.7	4.4	1.0	0.1	nil	9.1	1.1	0.5	nil	0.2	nil	289.9
ggH 1J Med	3.6	83.5	6.4	11.7	4.2	2.6	4.1	1.6	0.1	nil	1.9	0.4	0.6	nil	0.3	nil	156.2
ggH 1J High	0.7	76.0	1.9	17.5	1.1	3.4	1.4	2.7	0.1	0.1	0.3	0.3	0.2	nil	0.1	nil	31.5
ggH 1J BSM	nil	72.4	0.1	16.9	0.1	6.0	0.2	4.2	nil	0.3	nil	nil	nil	0.1	nil	nil	2.2
ggH 2J Low	1.8	79.1	2.7	9.6	3.7	4.5	4.1	3.1	2.2	1.1	5.4	2.3	3.9	0.3	1.9	nil	81.1
ggH 2J Med	1.5	77.6	3.1	12.2	3.2	4.4	3.8	3.2	2.6	1.5	1.6	0.7	4.5	0.4	2.4	nil	72.4
ggH 2J High	0.6	75.8	1.3	12.8	1.4	4.9	1.9	4.0	1.4	2.0	0.1	0.1	2.2	0.4	1.6	0.1	29.2
ggH 2J BSM	0.2	76.2	0.3	10.3	0.4	4.9	0.6	4.6	0.6	3.0	0.1	0.2	0.8	0.6	1.3	0.2	7.6
VBF Hjj Low loose	0.2	32.3	4.5	66.7	0.1	0.3	0.1	0.3	nil	nil	0.1	0.2	0.3	0.1	nil	nil	19.4
VBF Hjj Low tight	nil	12.9	4.2	86.7	nil	0.1	nil	0.1	nil	nil	nil	nil	0.3	0.1	nil	nil	13.8
VBF Hjj High loose	0.3	69.9	1.4	23.8	0.4	2.2	0.5	1.8	0.4	0.9	0.4	0.7	1.8	0.6	0.5	nil	16.5
VBF Hjj High tight	0.3	47.0	3.4	48.2	0.2	1.2	0.4	1.3	0.4	0.8	0.2	0.3	4.4	1.2	0.6	nil	20.2
VHhad loose	0.3	67.2	0.3	4.9	2.4	14.6	2.9	11.0	0.6	1.6	0.2	0.4	0.8	0.3	0.8	0.1	16.5
VHhad tight	0.2	52.4	0.1	3.4	3.0	23.8	3.5	18.0	0.6	1.9	nil	0.1	0.5	0.2	1.0	0.1	12.3
jet BSM	0.4	59.9	2.4	25.8	1.6	5.9	1.9	4.4	2.0	3.0	0.1	0.1	3.1	0.6	5.1	0.2	26.7
VHMET Low	nil	11.9	nil	0.4	0.1	23.4	0.6	63.2	nil	0.5	nil	0.3	nil	0.2	nil	nil	0.6
VHMET High	nil	1.3	nil	0.1	0.3	22.8	1.4	66.2	0.3	8.3	nil	nil	0.1	0.6	0.8	0.7	1.3
VHlep Low	nil	11.4	nil	1.1	4.4	68.0	0.8	8.1	1.3	8.5	0.2	0.9	1.8	1.6	2.2	0.4	6.4
VHlep High	nil	0.2	nil	nil	1.2	76.5	0.1	4.6	0.6	16.2	nil	nil	0.3	1.2	1.6	1.3	1.5
VHdilep	nil	nil	nil	nil	nil	nil	1.4	95.8	0.1	4.0	nil	nil	nil	nil	0.1	0.2	0.9
tHhad 4j2b	nil	23.8	nil	2.8	nil	1.6	0.1	13.5	0.6	39.0	0.1	8.2	1.2	10.5	0.3	0.6	0.6
tHhad 4j1b	nil	35.4	nil	4.0	0.1	4.3	0.3	7.9	2.2	36.3	0.2	2.2	3.8	8.5	2.6	1.3	2.5
ttHhadBDT4	nil	7.0	nil	0.8	nil	1.4	0.2	4.5	4.8	79.4	nil	0.3	1.9	4.3	4.7	2.4	2.5
ttHhadBDT3	nil	3.5	nil	0.5	nil	1.0	nil	3.1	1.3	86.1	nil	0.5	0.3	3.1	1.1	2.2	0.6
ttHhadBDT2	nil	3.6	nil	0.3	nil	0.8	nil	1.6	3.8	89.3	nil	0.2	0.6	1.8	3.4	2.4	1.8
ttHhadBDT1	nil	1.2	nil	0.1	nil	0.1	nil	0.7	3.4	95.0	nil	0.1	0.2	0.7	2.5	2.1	1.4
ttHlep	nil	nil	nil	nil	nil	0.2	nil	0.1	5.6	96.0	nil	0.1	0.4	1.0	5.0	2.6	2.4
tHlep 1fwd	nil	1.8	nil	0.2	nil	1.4	nil	0.9	2.1	79.4	nil	0.2	2.6	13.5	2.3	2.6	1.1
tHlep 0fwd	nil	4.1	nil	0.2	0.1	5.6	nil	2.8	1.9	75.7	nil	0.9	1.5	8.2	2.1	2.5	1.0
Total ϵ [%]	41.8	-	41.3	-	37.6	-	40.5	-	39.1	-	42.8	-	38.9	-	44.5	-	41.8
Events	1518.4		119.1		37.1		25.2		16.0		14.8		2.2		0.5		1733.2

Table. 4.7: Signal efficiencies times acceptance, ϵ , and expected signal event fractions per production mode, f , in each category for $\sqrt{s} = 13$ TeV and $m_h = 125.09$ GeV. The penultimate row shows the total efficiency per production process summed over the categories. Values labeled as “nil” correspond to efficiencies or fractions that are smaller than 0.05%. The total number of expected signal events, N_S , in the last row corresponds to an integrated luminosity of 36.1 fb^{-1} .

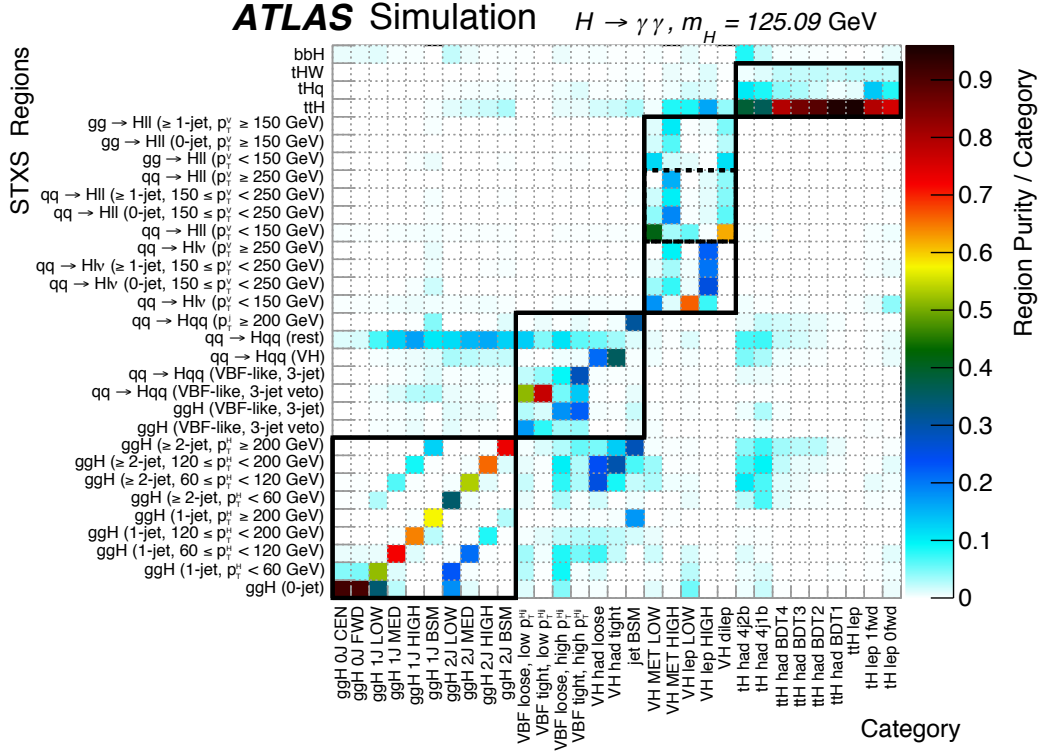


Fig. 4.13: Purity of the stage-1 STXS truth region of signal events (listed in y axis and Table 4.16) in each reconstructed category (listed in x axis and Table 4.6). The $t\bar{t}H$ and tH , VH leptonic, VH hadronic and VBF enriched, and untagged categories are separated by the black lines, as well as the STXS regions they are most sensitive to.

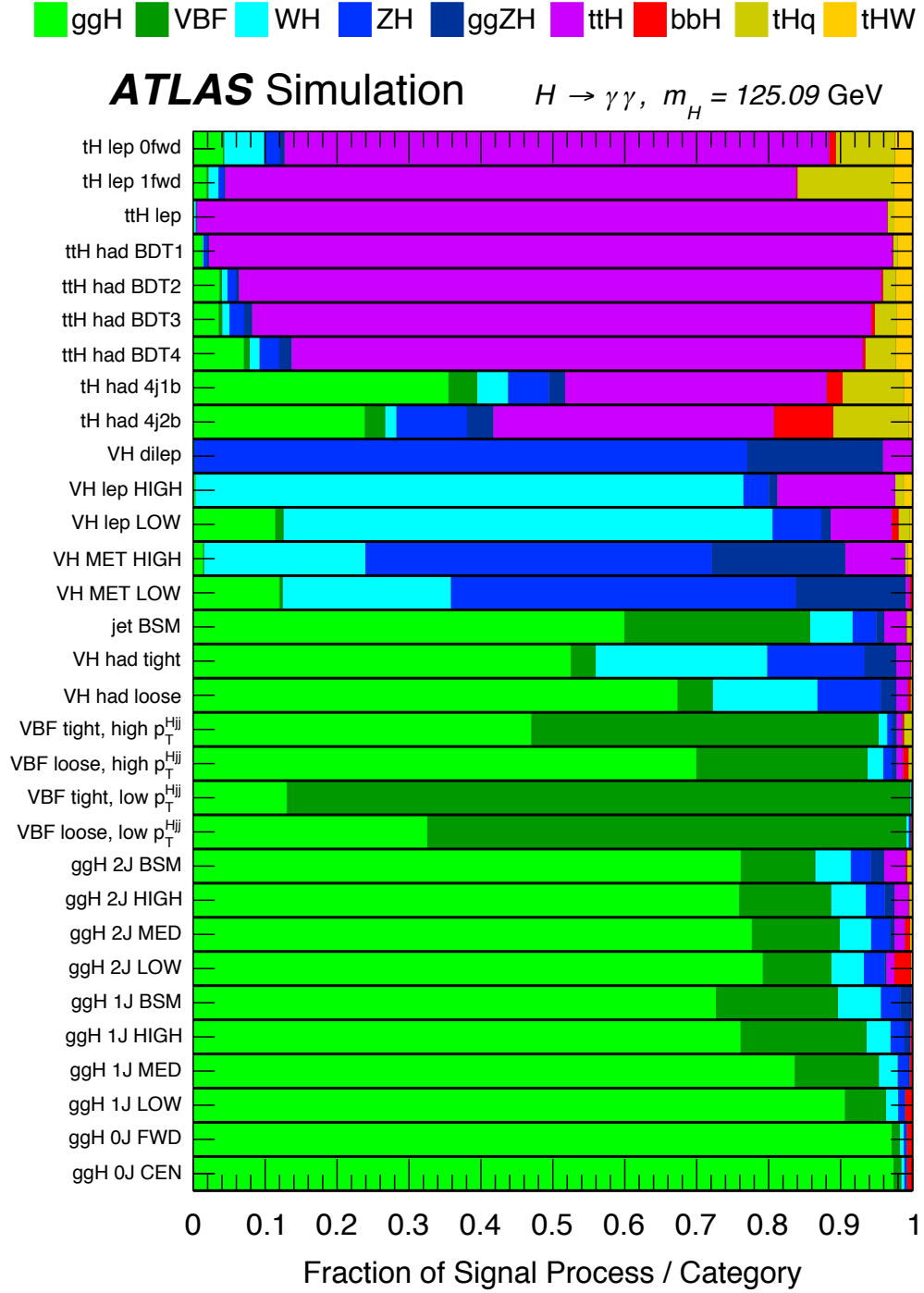


Fig. 4.14: Fraction of the selected Higgs boson events for each reconstructed category, in terms of the different production modes.

4.5 Data-MC comparison

In order to validate categorization, data to MC comparison is performed in all categories. 36.1 fb^{-1} data15 + data16 are used. The input signal samples are described in Table 4.1. The background samples are briefly listed here:

- Sherpa $\gamma\gamma$, ATLFast-II fast-simulation (Section 3.1);
- Sherpa $V\gamma\gamma$ simulation samples;
- Sherpa $V\gamma$ simulation samples, removing events overlapping with $V\gamma\gamma$ samples;
- Data-driven γj samples, reversing the ID requirement (not-tight) of 1 photon in data.

The normalization of QCD is based on the 2015+2016 $2\times 2\text{D}$ background decomposition [79] for the couplings categories. The theoretical prediction is used to normalize the rest of MC samples.

In addition to the genuine internal weights provided by the event generator, some extra corrections are applied to simulated events in order to improve data/MC agreement. In particular, the following corrections are applied:

- The MC samples are reweighted to match the pileup conditions of the dataset. This is done based on the distribution of average numbers of interactions per bunch crossing, $\langle\mu\rangle$.
- The width of the beam spot along the beam axis, σ_z , is slightly wider in the MC samples than in data. A reweighting is therefore applied to match the spread (and mean) of the beam spot observed in data.
- Shifts are applied to the photon shower shape variables and to the photon calorimeter isolation. Such shifts are determined as the average data-MC difference in photon-enriched control samples.
- Identification, reconstruction, and isolation efficiency scale factors for electrons and muons, identification and isolation efficiency scale factors for photons, and jet selection efficiency scale factors determined from data control samples are applied. Similarly, energy scale and resolution corrections for all simulated objects are also taken into account.

A relatively good agreement can be found for most of the distributions, except several categories for which lack of statistic.

4.5.1 Inclusive spectrum comparison

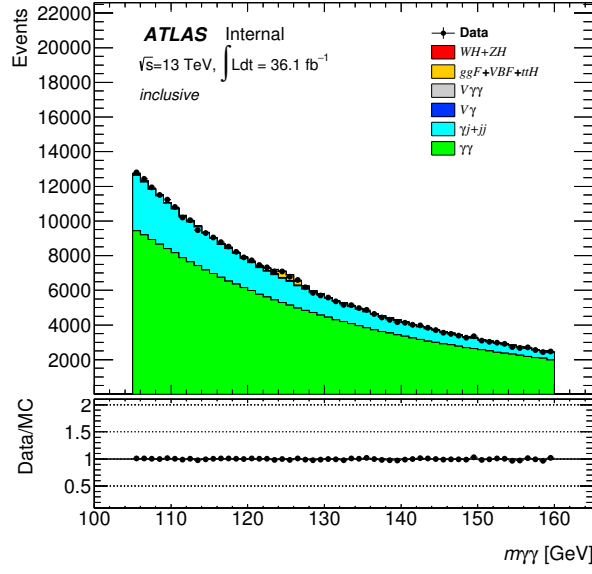


Fig. 4.15: Data/MC comparison of diphoton invariant mass spectrum.

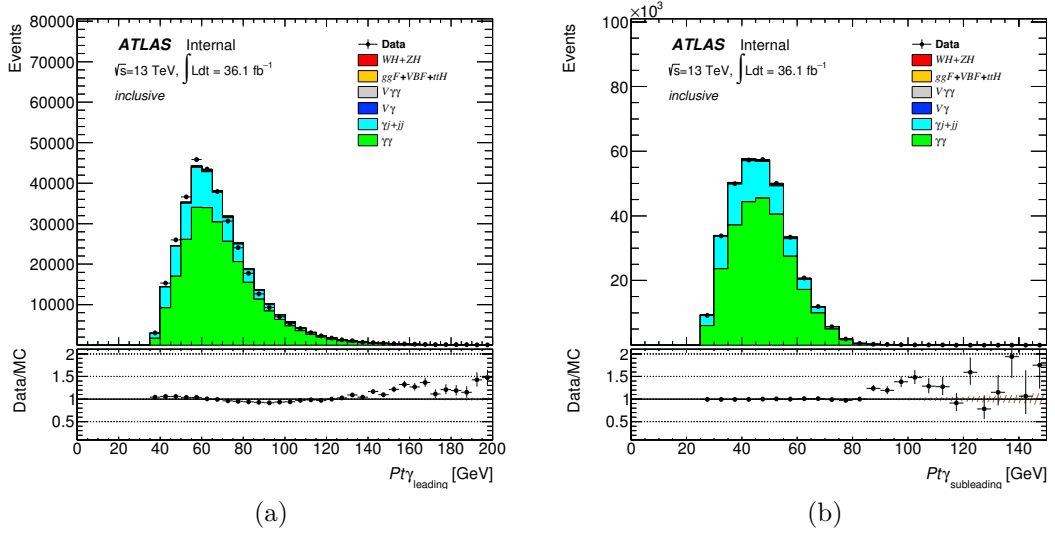


Fig. 4.16: Data/MC comparison of the p_T spectrum for (a) leading and (b) sub-leading photons.

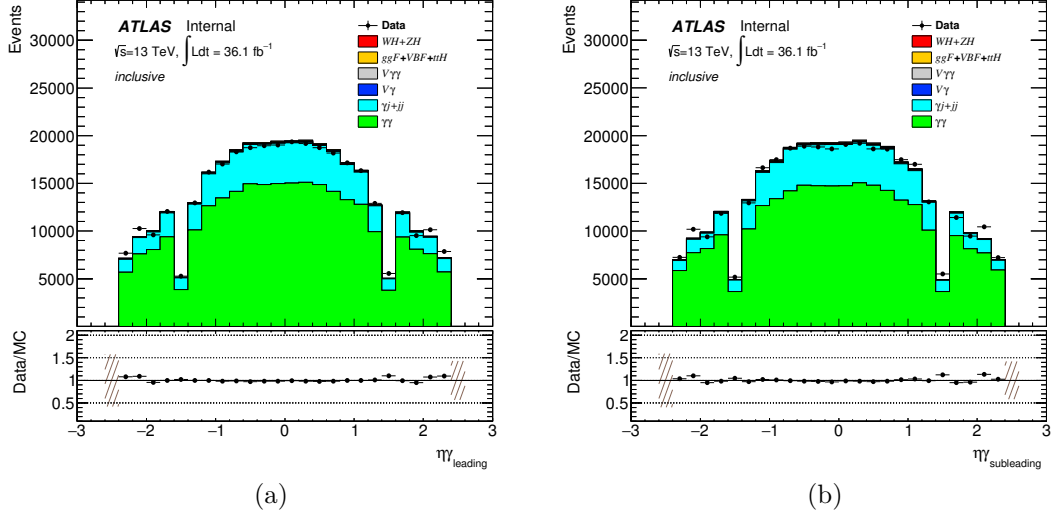


Fig. 4.17: Data/MC comparison of the η spectrum for (a) leading and (b) sub-leading photons.

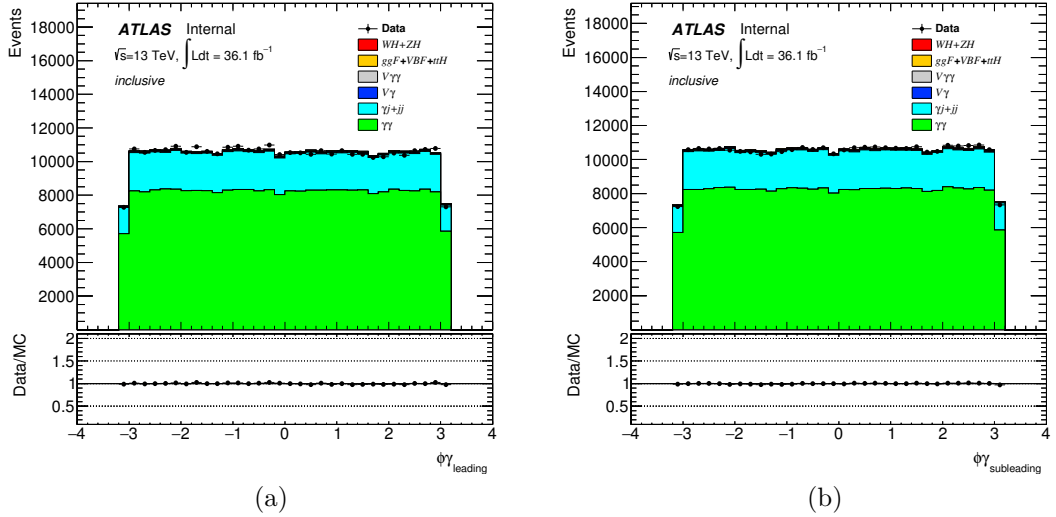


Fig. 4.18: Data/MC comparison of the ϕ spectrum for (a) leading and (b) sub-leading photons.

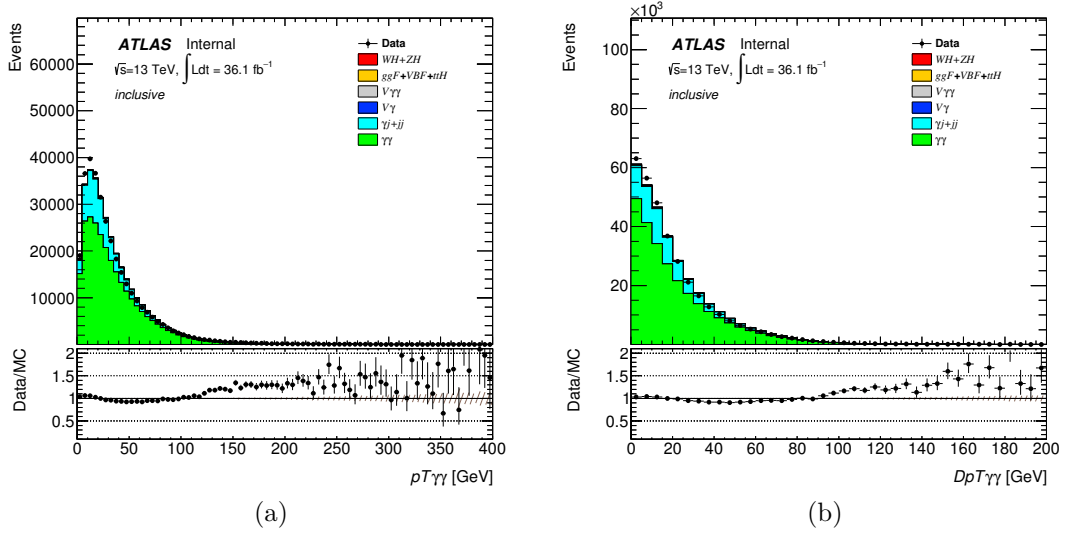


Fig. 4.19: Data/MC comparison of the spectrum for (a) diphoton p_T and (b) diphoton Δp_T .

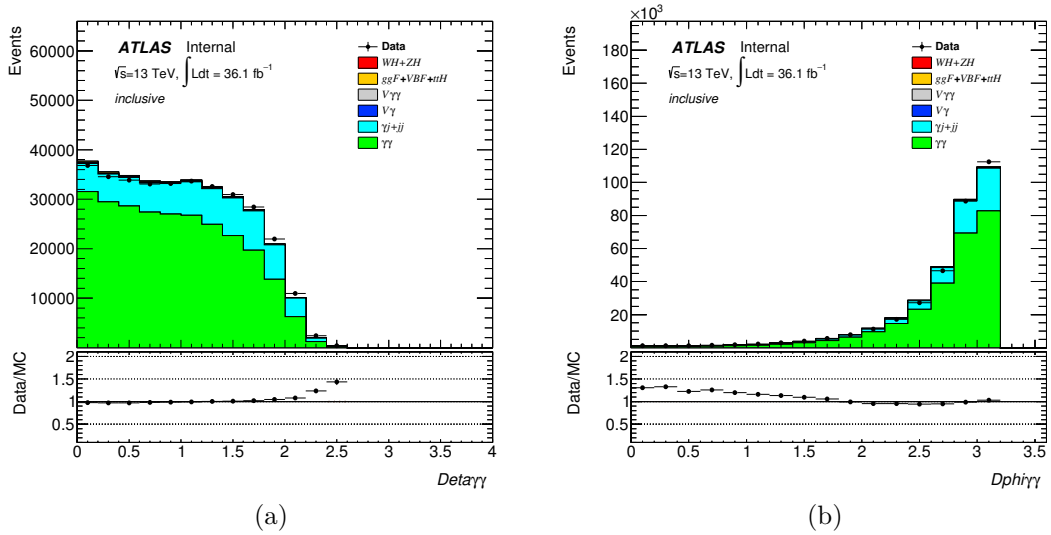


Fig. 4.20: Data/MC comparison of the spectrum for (a) diphoton $\Delta\eta$ and (b) diphoton $\Delta\phi$.

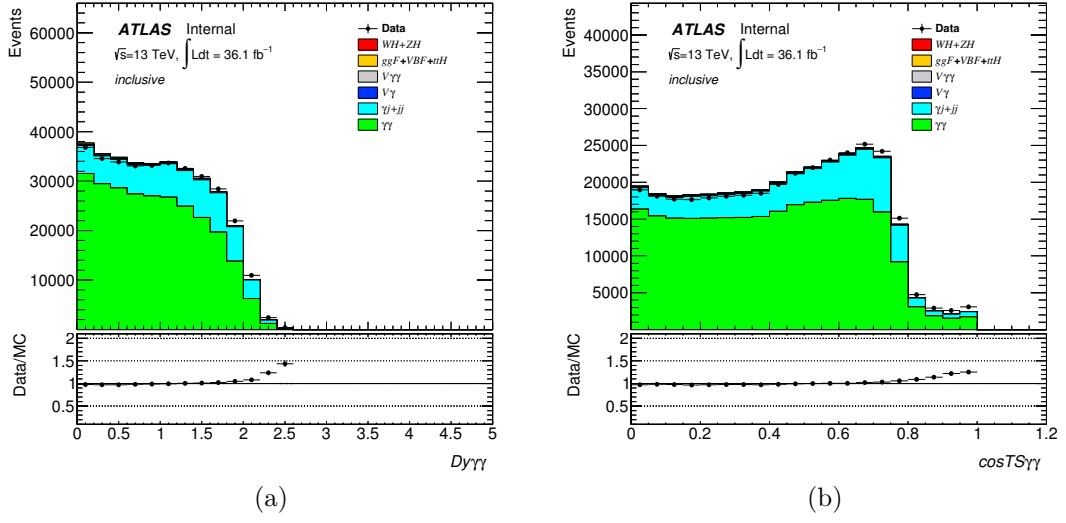


Fig. 4.21: Data/MC comparison of the spectrum for (a) diphoton Δy and (b) $|\cos \theta^*|$.

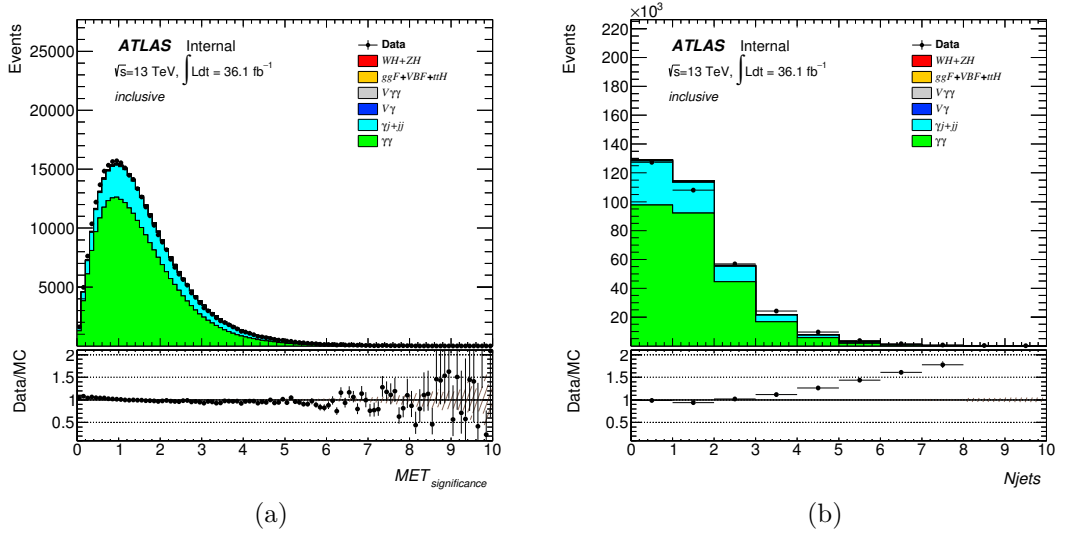


Fig. 4.22: Data/MC comparison of the spectrum for (a) E_T^{miss} significance and (b) jet multiplicity. Discrepancies up to 50% is found in the tail region of jet multiplicity. It's mainly due to the fact that data usually has more clusters and more associated tracks per jet than the simulation, giving difficulty in the modeling of the jet multiplicity.

4.5.2 diphoton mass spectrum data/MC comparison in selected categories

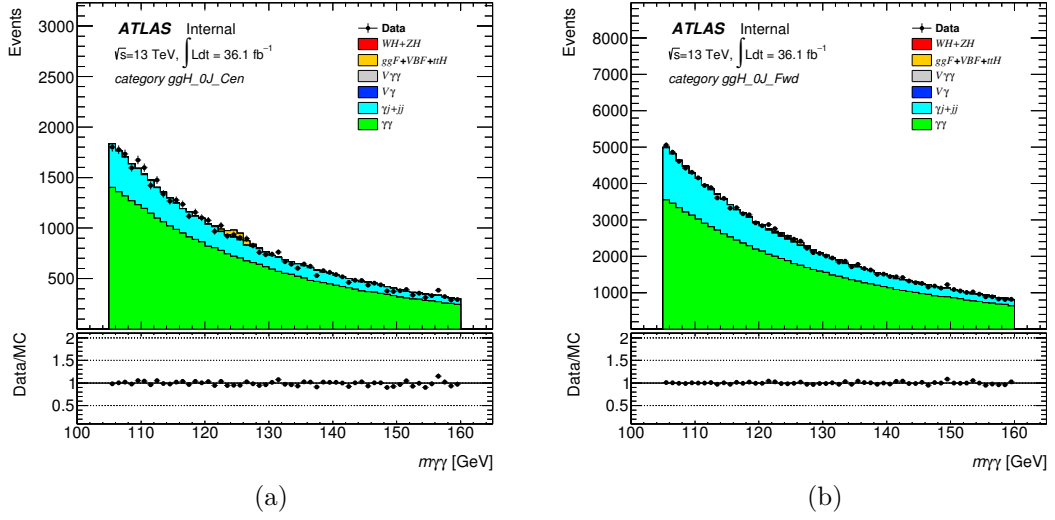


Fig. 4.23: Data/MC comparison of diphoton invariant mass spectrum for (a) ggH_{0J_Cen} and (b) ggH_{0J_Fwd} category.

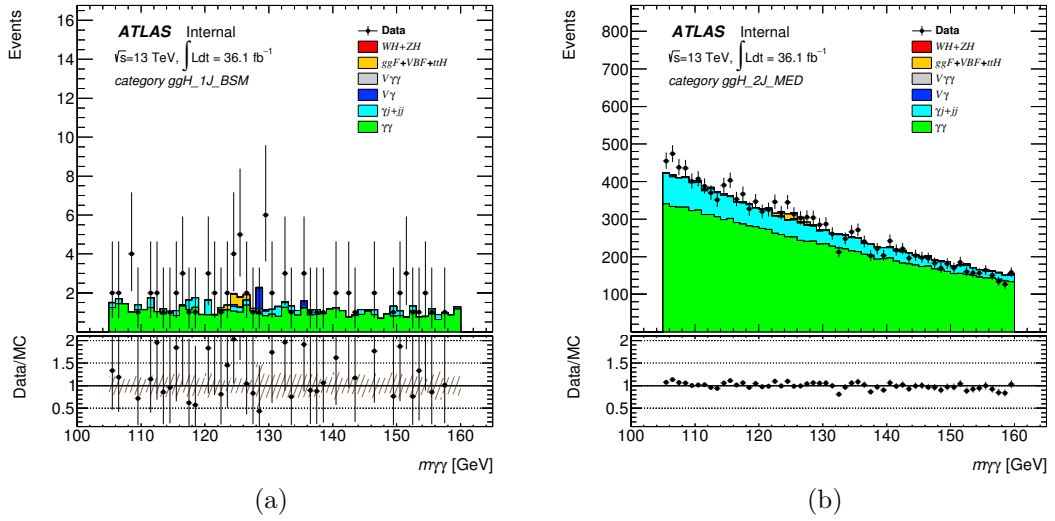


Fig. 4.24: Data/MC comparison of diphoton invariant mass spectrum for (a) ggH_{1J_BSM} and (b) ggH_{2J_MET} category.

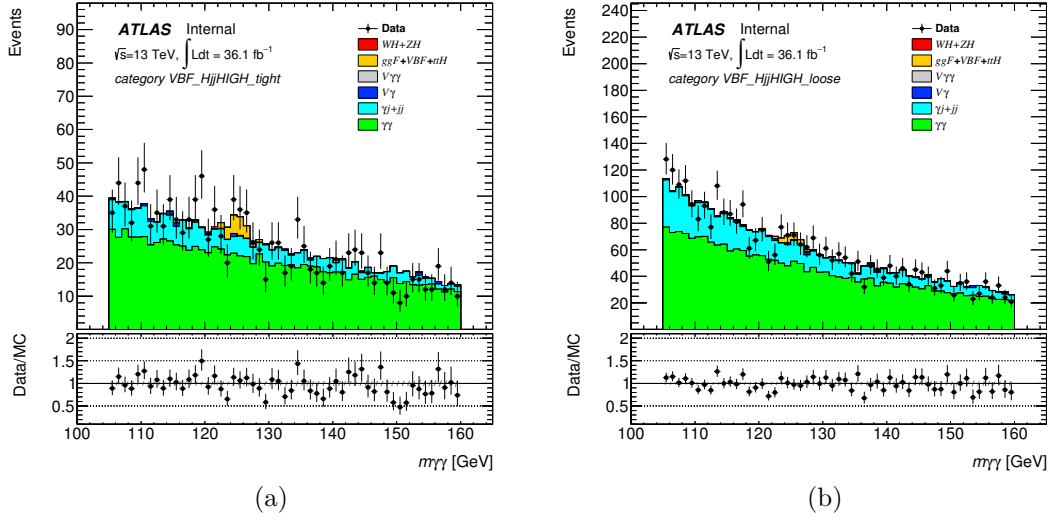


Fig. 4.25: Data/MC comparison of diphoton invariant mass spectrum for (a) VBF_HjjHIGH and (b) VBF_HjjHIGH category.

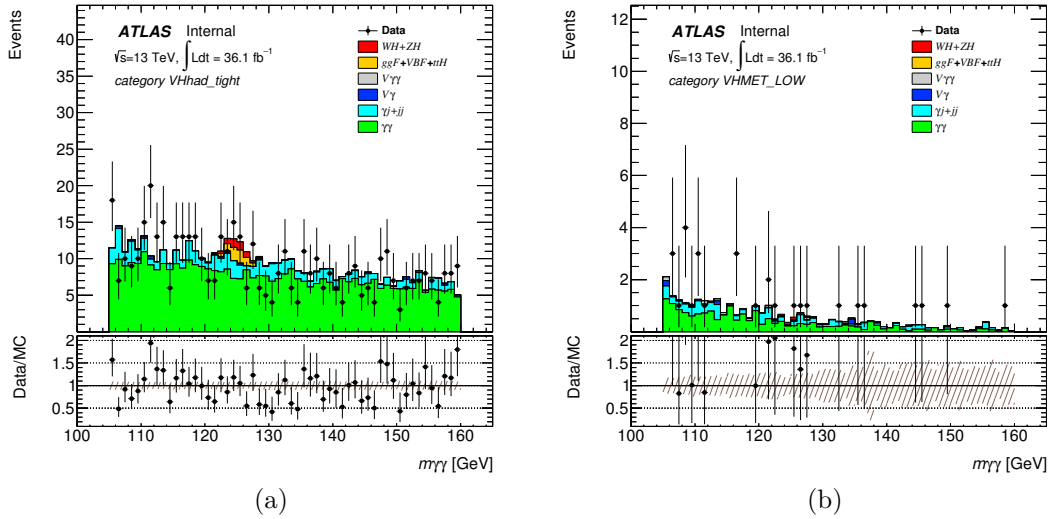


Fig. 4.26: Data/MC comparison of diphoton invariant mass spectrum for (a) VH_had_tight and (b) VHMET_LOW category.

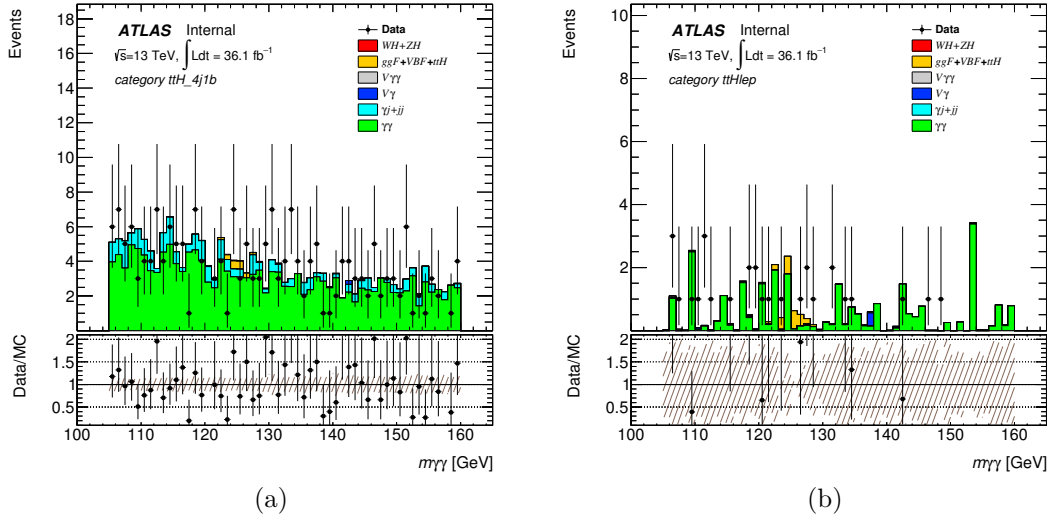


Fig. 4.27: Data/MC comparison of diphoton invariant mass spectrum for (a) ttH_4j1b and (b) $ttHlep$ category.

4.6 Signal and background modeling

With an unbinned maximum-likelihood fit to the $m_{\gamma\gamma}$ spectrum for each reconstruction category (Section 4.4), the Higgs boson signal can be extracted. The signal model, based on MC simulation for the various production modes of the Higgs boson, is developed for each category of the analysis, and the background model parameters are floated in the fit to the $m_{\gamma\gamma}$ spectra. The mass range $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$ is chosen to allow a reliable determination of the background from the data, and to avoid large uncertainties from the choice of the background parameterization. The modeling of signal and background shapes are described in this section.

4.6.1 Signal model

Thanks to the excellent photon energy resolution, a narrow peak appears in the $m_{\gamma\gamma}$ spectrum coming from the Higgs boson signal.

For the shape, an analytic description of the signal shape in $m_{\gamma\gamma}$ is necessary in order to perform an unbinned maximum likelihood fit on the data. Several functional forms have been considered in order to model the resonance shape:

- A Crystal Ball (Equation 4.7) plus Gaussian Probability Density Function (PDF), with:

$$f_{\text{CB}}(x) = N \begin{cases} \exp\left(-\frac{(x-\mu_{\text{CB}})^2}{2\sigma_{\text{CB}}^2}\right) & \text{if } x > \mu_{\text{CB}} - \alpha\sigma_{\text{CB}} \\ A \left(B - \frac{(x-\mu_{\text{CB}})}{\sigma_{\text{CB}}}\right)^n & \text{if } x \leq \mu_{\text{CB}} - \alpha\sigma_{\text{CB}} \end{cases} \quad (4.7)$$

In equation 4.7, N is a normalization constant, A and B are determined in such a way that the function is continuous and depend only on the four CB parameters: μ_{CB} , σ_{CB} , α and n . The shape parameters are common to all processes (ggH , VBF , VH , ttH), and a global fit with all processes is performed for each category.

- A double-sided Crystal Ball (Equation 4.8) PDF

$$f_{\text{DCB}}(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \leq t \leq \alpha_{\text{high}} \\ \frac{e^{-\frac{1}{2}\alpha_{\text{low}}^2}}{\left[\frac{1}{R_{\text{low}}}(R_{\text{low}} - \alpha_{\text{low}} - t)\right]^{n_{\text{low}}}} & \text{if } t < -\alpha_{\text{low}} \\ \frac{e^{-\frac{1}{2}\alpha_{\text{high}}^2}}{\left[\frac{1}{R_{\text{high}}}(R_{\text{high}} - \alpha_{\text{high}} + t)\right]^{n_{\text{high}}}} & \text{if } t > \alpha_{\text{high}} \end{cases} \quad (4.8)$$

In equation 4.8, $t = (m_{\gamma\gamma} - \mu_{CB})/\sigma_{CB}$, $R_{\text{low}} = \frac{n_{\text{low}}}{\alpha_{\text{low}}}$, and $R_{\text{high}} = \frac{n_{\text{high}}}{\alpha_{\text{high}}}$. For these equations, N is a normalization parameter, μ_{CB} , represents the peak, σ_{CB} is the width, α_{low} and α_{high} are the positions of the transitions from the Gaussian core and the exponential tails on the low and high mass sides, and n_{low} and n_{high} are the exponents of the low and high-mass tails. The shape parameters are common to all processes (ggH , VBF , VH , ttH), and a global fit with all processes is performed for each category.

A comparison between double-sided Crystal Ball and Crystal Ball + Gaussian signal shape is performed for all categories. Fit results are shown in Figure 4.28.

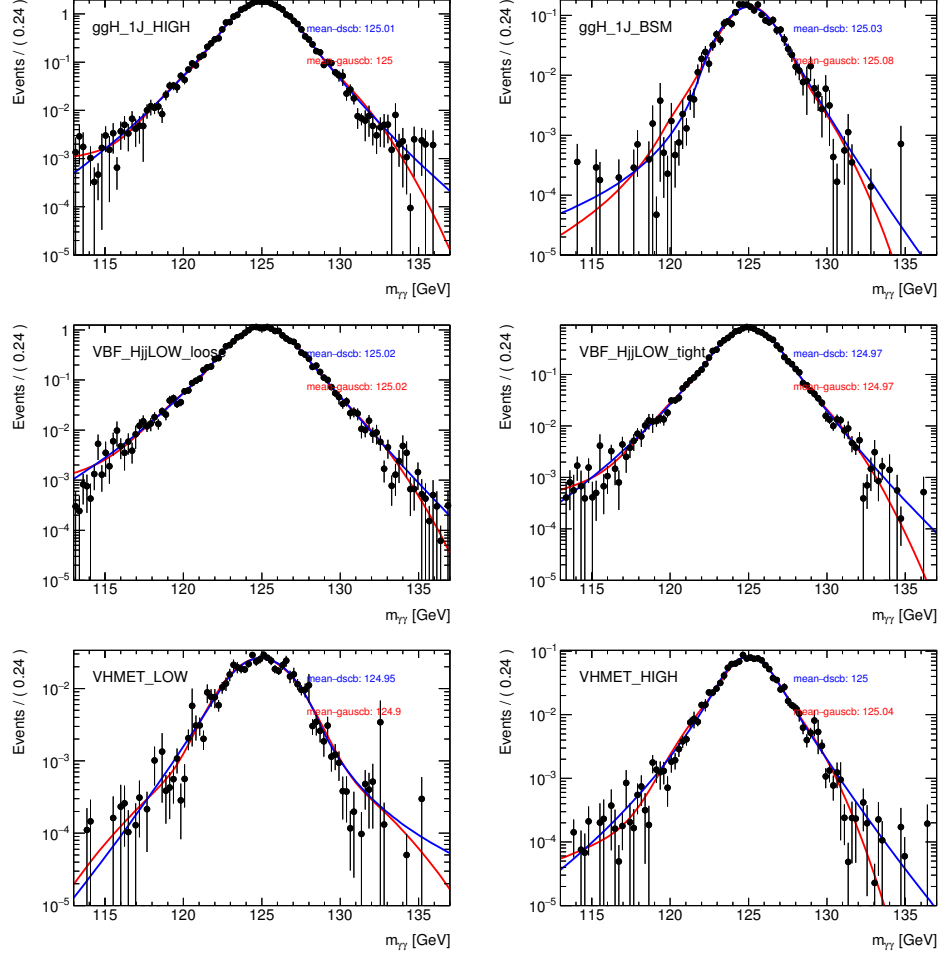


Fig. 4.28: Comparison of unbin fit on the signal model between a Double-sided Crystal Ball model (blue) and a Crystal Ball+Gaussian model (red) for reconstructed categories.

From this comparison, the fit value of diphoton invariant mass is similar, though, Double Side Crystal Ball functions perform better in most of reconstructed categories, especially for tail regions.

By fitting to the simulated signal samples in each reconstructed category, the parameters of the Double-sided Crystal function are defined. Figure 4.29 shows an example of two representing categories, which are the central region of the detector (defined by requiring $|\eta| \leq 0.95$ for both selected photons) with the most improved resolution, and the forward region (defined by requiring one photon with $|\eta| \leq 0.95$ and one photon with $0.95 < |\eta| < 2.37$) with the largest resolution number. The effective signal mass resolution of the two categories, defined as half the width containing 68% (90%) of the signal events, is 1.6 (2.7) GeV and 2.1 (3.8) GeV, respectively.

Table 4.8 presents the resolution for the signal shape in each reconstructed category.

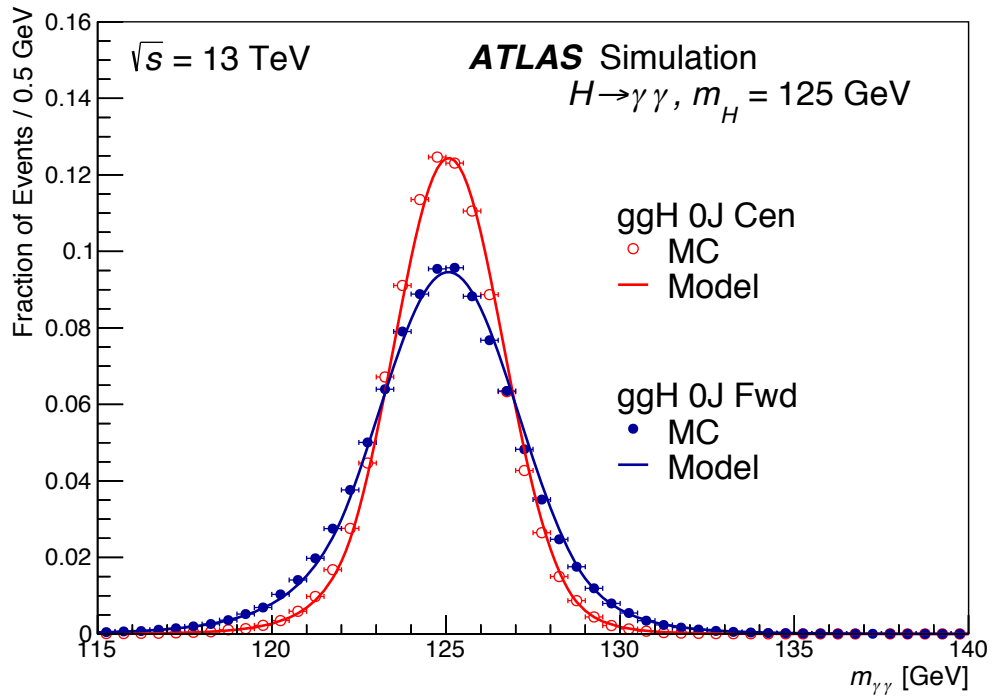


Fig. 4.29: Diphoton invariant mass signal shapes of ggH 0J Fwd and ggH 0J Cen categories that introduced in Section 4.4. The simulated events are generated with $m_h = 125 \text{ GeV}$ from all Higgs boson production processes.

Category	$\sqrt{s}=13$ TeV	
	σ_{68} [GeV]	σ_{90} [GeV]
ggH 0J Cen	1.61	2.73
ggH 0J Fwd	2.14	3.78
ggH 1J Low	1.91	3.38
ggH 1J Med	1.82	3.20
ggH 1J High	1.63	2.91
ggH 1J BSM	1.44	2.57
ggH 2J Low	1.92	3.42
ggH 2J Med	1.82	3.24
ggH 2J High	1.64	2.94
ggH 2J BSM	1.42	2.60
VBH Hjj Low loose	1.84	3.30
VBH Hjj Low tight	1.64	2.93
VBH Hjj High loose	1.80	3.18
VBH Hjj High tight	1.66	2.99
VHhad loose	1.71	3.11
VHhad tight	1.54	2.75
qqH BSM	1.42	2.59
VHMET Low	1.83	3.26
VHMET High	1.56	2.75
VHlep Low	1.78	3.28
VHlep High	1.52	2.75
VHdilep	1.74	3.03
ttHhad 4j2b	1.70	3.06
ttHhad 4j1b	1.66	2.96
tthHadBDT4	1.63	2.92
tthHadBDT3	1.62	2.92
tthHadBDT2	1.59	2.89
tthHadBDT1	1.60	2.84
ttHlep	1.62	2.85
tHlep 1fwd	1.72	2.99
tHlep 0fwd	1.67	2.98
Inclusive Cen	1.87	3.32

Table. 4.8: Effective signal mass resolutions σ_{68} and σ_{90} for $\sqrt{s} = 13$ TeV data in each event category, where σ_{68} (σ_{90}) is defined as half of the smallest interval expected to contain 68% (90%) of the signal events for a mass $m_h = 125.09$ GeV.

4.6.2 Background composition and model

4.6.2.1 Background composition

The dominant background entering the invariant mass spectrum is from SM continuum diphoton production. There are also significant backgrounds from photon-jet production and dijet production, since energetic π^0 s from jet fragmentation can fake photons. Finally, Drell-Yan events where both electrons are misidentified as photons contribute a small fraction ($< 1\%$) to the total background. The background composition is used for constructing the background templates.

To measure the relative background fractions of $\gamma\gamma$, γj and jj in data for each category, a double two-dimensional sideband method [79] is used. Data are split into 16 orthogonal regions defined by diphoton pairs in which one or both photons satisfying/failing the nominal/loosened identification and isolation requirement. The signal region, where both photons satisfy the nominal identification and isolation requirements, can be disentangled by considering the $\gamma\gamma$, γj and jj yields and the efficiencies for photons and for hadronic jets passing identification and isolation selections in other 15 control regions.

The fractions of background sources in the inclusive diphoton sample are $(78.7^{+1.8}_{-5.2})\%$, $(18.6^{+4.2}_{-1.6})\%$ and $(2.6^{+0.5}_{-0.4})\%$ for $\gamma\gamma$, γj and jj , respectively. The uncertainties are systematically dominated. The systematic uncertainties on the background composition are estimated by considering the following three sources: variations on the definition of the background control region, the modeling of the isolation efficiencies, the tight identification efficiencies. The variation introducing the maximal deviation from the nominal definition is taken as the systematic uncertainty.

Table 4.9 gives the obtained $\gamma\gamma$, γj and jj event yields and fractional decomposition for each category.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γj	jj	$\gamma\gamma$	γj	jj
Coupling Cat.						
Baseline	261468 $\pm$ 718 $^{+1254}_{-15117}$	62307 $\pm$ 448 $^{+11538}_{-341}$	8633 $\pm$ 103 $^{+3134}_{-604}$	78.7 $\pm$ 0.2 $^{+0.3}_{-4.4}$	18.7 $\pm$ 0.2 $^{+3.5}_{-0.1}$	2.6 $\pm$ 0.0 $^{+0.9}_{-0.2}$
ggH 0J Cen	40885 $\pm$ 273 $^{+1988}_{-294}$	9748 $\pm$ 150 $^{+343}_{-1523}$	1068 $\pm$ 22 $^{+53}_{-479}$	79.1 $\pm$ 0.3 $^{+3.9}_{-0.7}$	18.9 $\pm$ 0.3 $^{+0.6}_{-2.9}$	2.1 $\pm$ 0.1 $^{+0.1}_{-0.9}$
ggH 0J Fwd	105270 $\pm$ 484 $^{+844}_{-8567}$	30546 $\pm$ 330 $^{+6211}_{-323}$	5161 $\pm$ 84 $^{+2052}_{-311}$	74.7 $\pm$ 0.3 $^{+0.5}_{-5.9}$	21.7 $\pm$ 0.3 $^{+4.5}_{-0.3}$	3.7 $\pm$ 0.1 $^{+1.5}_{-0.2}$
ggH 1J LOW	50365 $\pm$ 308 $^{+538}_{-4340}$	10736 $\pm$ 185 $^{+3640}_{-371}$	1355 $\pm$ 41 $^{+523}_{-90}$	80.6 $\pm$ 0.3 $^{+0.7}_{-6.7}$	17.2 $\pm$ 0.3 $^{+5.9}_{-0.6}$	2.2 $\pm$ 0.1 $^{+0.8}_{-0.1}$
ggH 1J MED	19458 $\pm$ 184 $^{+188}_{-1005}$	3648 $\pm$ 101 $^{+918}_{-140}$	281 $\pm$ 19 $^{+49}_{-129}$	83.2 $\pm$ 0.5 $^{+0.6}_{-4.2}$	15.6 $\pm$ 0.5 $^{+4.0}_{-0.6}$	1.2 $\pm$ 0.1 $^{+0.2}_{-0.6}$
ggH 1J HIGH	1984 $\pm$ 57 $^{+0}_{-119}$	324 $\pm$ 28 $^{+105}_{-0}$	12 $\pm$ 4 $^{+9}_{-5}$	85.5 $\pm$ 1.4 $^{+0.0}_{-4.9}$	14.0 $\pm$ 1.4 $^{+4.5}_{-0.0}$	0.5 $\pm$ 0.2 $^{+0.4}_{-0.2}$
ggH 1J BSM	70 $\pm$ 14 $^{+8}_{-121}$	18 $\pm$ 10 $^{+117}_{-7}$	1 $\pm$ 1 $^{+15}_{-1}$	79.0 $\pm$ 12.5 $^{+8.8}_{-136.9}$	20.3 $\pm$ 12.4 $^{+131.1}_{-7.7}$	0.7 $\pm$ 1.2 $^{+17.1}_{-1.0}$
ggH 2J LOW	20110 $\pm$ 185 $^{+185}_{-1096}$	3353 $\pm$ 107 $^{+779}_{-87}$	450 $\pm$ 24 $^{+306}_{-57}$	84.1 $\pm$ 0.5 $^{+0.6}_{-4.5}$	14.0 $\pm$ 0.5 $^{+3.3}_{-0.4}$	1.9 $\pm$ 0.1 $^{+1.3}_{-0.2}$
ggH 2J MED	12021 $\pm$ 138 $^{+60}_{-462}$	1772 $\pm$ 74 $^{+295}_{-173}$	194 $\pm$ 14 $^{+148}_{-53}$	85.9 $\pm$ 0.6 $^{+0.6}_{-3.1}$	12.7 $\pm$ 0.6 $^{+2.1}_{-1.2}$	1.4 $\pm$ 0.1 $^{+1.1}_{-0.4}$
ggH 2J HIGH	2364 $\pm$ 59 $^{+17}_{-134}$	309 $\pm$ 28 $^{+137}_{-9}$	14 $\pm$ 4 $^{+0}_{-15}$	88.0 $\pm$ 1.2 $^{+0.4}_{-4.7}$	11.5 $\pm$ 1.2 $^{+5.2}_{-0.4}$	0.5 $\pm$ 0.2 $^{+0.0}_{-0.5}$
ggH 2J BSM	257 $\pm$ 19 $^{+16}_{-9}$	45 $\pm$ 8 $^{+10}_{-16}$	0 $\pm$ 0 $^{+2}_{-0}$	85.2 $\pm$ 3.1 $^{+4.9}_{-3.6}$	14.8 $\pm$ 3.1 $^{+3.1}_{-5.3}$	0.1 $\pm$ 0.1 $^{+0.0}_{-0.0}$
VBF HjjLOW loose	743 $\pm$ 36 $^{+0}_{-52}$	147 $\pm$ 20 $^{+38}_{-0}$	12 $\pm$ 4 $^{+9}_{-1}$	82.4 $\pm$ 2.6 $^{+0.0}_{-5.3}$	16.3 $\pm$ 2.6 $^{+4.3}_{-0.0}$	1.3 $\pm$ 0.5 $^{+1.0}_{-0.2}$
VBF HjjLOW tight	112 $\pm$ 14 $^{+13}_{-0}$	22 $\pm$ 7 $^{+0}_{-26}$	2 $\pm$ 1 $^{+14}_{-0}$	82.4 $\pm$ 6.2 $^{+9.6}_{-0.0}$	16.2 $\pm$ 6.1 $^{+0.0}_{-19.2}$	1.4 $\pm$ 1.0 $^{+10.3}_{-0.0}$
VBF HjjHIGH loose	1631 $\pm$ 55 $^{+19}_{-143}$	330 $\pm$ 33 $^{+138}_{-0}$	54 $\pm$ 8 $^{+1}_{-29}$	80.9 $\pm$ 1.9 $^{+0.8}_{-0.0}$	16.4 $\pm$ 1.8 $^{+6.9}_{-0.0}$	2.7 $\pm$ 0.5 $^{+0.1}_{-0.0}$
VBF HjjHIGH tight	917 $\pm$ 39 $^{+18}_{-22}$	146 $\pm$ 21 $^{+30}_{-28}$	20 $\pm$ 5 $^{+12}_{-6}$	84.7 $\pm$ 2.3 $^{+1.5}_{-2.2}$	13.5 $\pm$ 2.2 $^{+2.7}_{-2.6}$	1.8 $\pm$ 0.5 $^{+1.1}_{-0.5}$
VHhad loose	1632 $\pm$ 52 $^{+22}_{-116}$	244 $\pm$ 28 $^{+125}_{-12}$	23 $\pm$ 5 $^{+0}_{-19}$	85.9 $\pm$ 1.7 $^{+1.2}_{-5.7}$	12.9 $\pm$ 1.6 $^{+6.7}_{-0.7}$	1.2 $\pm$ 0.3 $^{+0.0}_{-1.0}$
VHhad tight	406 $\pm$ 25 $^{+5}_{-28}$	64 $\pm$ 12 $^{+29}_{-2}$	3 $\pm$ 2 $^{+0}_{-3}$	85.8 $\pm$ 3.0 $^{+1.0}_{-5.9}$	13.6 $\pm$ 3.0 $^{+6.2}_{-0.4}$	0.6 $\pm$ 0.4 $^{+0.0}_{-0.6}$
qqH BSM	2540 $\pm$ 64 $^{+179}_{-0}$	361 $\pm$ 29 $^{+9}_{-166}$	13 $\pm$ 4 $^{+5}_{-16}$	87.2 $\pm$ 1.2 $^{+6.2}_{-0.0}$	12.4 $\pm$ 1.2 $^{+0.0}_{-5.7}$	0.4 $\pm$ 0.2 $^{+0.2}_{-0.5}$
VHMET LOW	15 $\pm$ 6 $^{+10}_{-9}$	9 $\pm$ 4 $^{+9}_{-12}$	2 $\pm$ 1 $^{+3}_{-0}$	58.2 $\pm$ 20.1 $^{+40.9}_{-32.1}$	35.0 $\pm$ 19.5 $^{+33.8}_{-47.4}$	6.7 $\pm$ 5.8 $^{+13.1}_{-1.7}$
VHMET HIGH BSM	20 $\pm$ 6 $^{+0}_{-8}$	3 $\pm$ 4 $^{+12}_{-0}$	2 $\pm$ 3 $^{+0}_{-4}$	79.8 $\pm$ 21.6 $^{+0.0}_{-35.4}$	12.6 $\pm$ 17.8 $^{+49.1}_{-0.0}$	7.5 $\pm$ 14.4 $^{+0.0}_{-14.7}$
VHlep LOW	359 $\pm$ 25 $^{+0}_{-94}$	46 $\pm$ 15 $^{+111}_{-0}$	11 $\pm$ 3 $^{+0}_{-18}$	86.3 $\pm$ 3.9 $^{+0.0}_{-22.4}$	11.1 $\pm$ 3.8 $^{+26.8}_{-0.0}$	2.6 $\pm$ 0.9 $^{+0.0}_{-4.4}$
VHlep HIGH	23 $\pm$ 18 $^{+0}_{-4}$	1 $\pm$ 1 $^{+1}_{-0}$	0 $\pm$ 0 $^{+2}_{-0}$	95.1 $\pm$ 9.6 $^{+0.0}_{-13.1}$	4.8 $\pm$ 9.4 $^{+4.7}_{-1.2}$	0.0 $\pm$ 1.4 $^{+9.2}_{-0.0}$
VHdilep LOW HIGH	8 $\pm$ 7 $^{+0}_{-7}$	1 $\pm$ 2 $^{+3}_{-0}$	1 $\pm$ 1 $^{+0}_{-1}$	83.2 $\pm$ 32.0 $^{+0.0}_{-34.4}$	8.5 $\pm$ 24.2 $^{+44.5}_{-0.0}$	8.3 $\pm$ 18.6 $^{+0.0}_{-13.1}$
ttH Had 6j2b	48 $\pm$ 9 $^{+8}_{-14}$	11 $\pm$ 5 $^{+14}_{-8}$	0 $\pm$ 0 $^{+1}_{-0}$	80.5 $\pm$ 10.1 $^{+12.3}_{-23.6}$	19.1 $\pm$ 10.1 $^{+23.9}_{-13.4}$	0.4 $\pm$ 0.5 $^{+1.1}_{-0.6}$
ttH Had 6j1b	378 $\pm$ 24 $^{+5}_{-33}$	42 $\pm$ 12 $^{+32}_{-3}$	6 $\pm$ 1 $^{+0}_{-4}$	88.8 $\pm$ 3.2 $^{+1.8}_{-6.7}$	9.8 $\pm$ 3.1 $^{+7.6}_{-1.3}$	1.5 $\pm$ 0.4 $^{+0.0}_{-0.9}$
ttH Had 5j2b	114 $\pm$ 12 $^{+6}_{-4}$	9 $\pm$ 5 $^{+3}_{-6}$	0 $\pm$ 0 $^{+2}_{-0}$	92.1 $\pm$ 4.5 $^{+3.8}_{-2.9}$	7.6 $\pm$ 4.5 $^{+2.8}_{-5.1}$	0.3 $\pm$ 0.2 $^{+1.4}_{-0.0}$
ttH Had 5j1b	20 $\pm$ 5 $^{+0}_{-12}$	1 $\pm$ 2 $^{+9}_{-0}$	0 $\pm$ 0 $^{+3}_{-0}$	93.3 $\pm$ 10.3 $^{+0.0}_{-54.3}$	6.2 $\pm$ 10.2 $^{+39.2}_{-0.0}$	0.5 $\pm$ 1.0 $^{+15.8}_{-0.7}$
ttH Had 4j2b	31 $\pm$ 7 $^{+4}_{-11}$	6 $\pm$ 4 $^{+7}_{-4}$	0 $\pm$ 0 $^{+4}_{-0}$	82.0 $\pm$ 12.3 $^{+11.3}_{-29.0}$	16.9 $\pm$ 12.2 $^{+18.5}_{-11.5}$	1.0 $\pm$ 1.4 $^{+11.5}_{-0.0}$
ttH Had 4j1b	0 $\pm$ 16 $^{+29}_{-0}$	21 $\pm$ 33 $^{+0}_{-31}$	0 $\pm$ 1 $^{+8}_{-0}$	0.0 $\pm$ 77.5 $^{+141.9}_{-0.0}$	99.8 $\pm$ 77.8 $^{+0.0}_{-147.8}$	0.2 $\pm$ 3.1 $^{+39.0}_{-0.0}$
ttH Lep	27 $\pm$ 19 $^{+2}_{-1}$	1 $\pm$ 1 $^{+0}_{-1}$	0 $\pm$ 0 $^{+2}_{-0}$	97.5 $\pm$ 6.1 $^{+2.7}_{-4.1}$	2.5 $\pm$ 6.1 $^{+0.0}_{-4.7}$	0.0 $\pm$ 0.0 $^{+7.7}_{-0.0}$
ttH Lep 0fwd	0 $\pm$ 10 $^{+32}_{-0}$	18 $\pm$ 15 $^{+0}_{-30}$	1 $\pm$ 4 $^{+0}_{-2}$	0.0 $\pm$ 51.7 $^{+166.6}_{-0.0}$	94.3 $\pm$ 56.7 $^{+0.0}_{-159.3}$	5.7 $\pm$ 24.1 $^{+0.0}_{-9.3}$
ttH Lep 1fwd	27 $\pm$ 7 $^{+3}_{-2}$	7 $\pm$ 4 $^{+2}_{-3}$	0 $\pm$ 0 $^{+0}_{-0}$	78.3 $\pm$ 13.9 $^{+8.4}_{-5.3}$	21.7 $\pm$ 13.9 $^{+5.2}_{-9.2}$	0.0 $\pm$ 0.0 $^{+1.1}_{-0.0}$

Table. 4.9: $\gamma\gamma$, γj and jj yields and fraction decomposition in each category after the final selection, obtained from the 2 $\times$ 2D Sideband Method. The small Drell-Yan contribution is included in the $\gamma\gamma$ yields and fractions.

4.6.2.2 Background modeling

The $m_{\gamma\gamma}$ distribution of background contributions in each category is parametrized with an analytic function, where the normalization and function parameters are obtained from fits to the $m_{\gamma\gamma}$ distribution on data. The choice of fit function is made in each category using either MC or data-driven background samples. After measuring the bias associated to each function, the function with the smallest number of degrees of freedom that satisfies the bias criteria is chosen.

The bias for a given background parameterization (function) is typically estimated using a representative background MC sample with data-driven corrections. $\gamma\gamma$ fast simulation samples and $\gamma j + jj$ from reverse-ID data are used for most of the categories except $t\bar{t}H$ and VH non-hadronic. In the case of $t\bar{t}H$ categories, where too many MC samples would be required to model the background and the normalization of each is not well known, the function bias is determined in data control regions. The $V\gamma\gamma$ samples are used in the VH non-hadronic categories.

These background-only samples are fit with a function combining the background parameterization and the signal model; the fitted number of signal events is then a measure of the signal bias. The fit is performed in the same mass range as that of the analysis, $[105, 160]$ GeV. Values of m_h ranging from 121 GeV to 129 GeV are scanned in steps of 1 GeV, and the fit bias (referred to as the “spurious” signal in the following) is evaluated as the maximum value of $|N_s|$ over this range:

$$N_{sp} = \max_{121 < m_h < 129 \text{ GeV}} |N_s(m_h)|.$$

The spurious signal N_{SP} is required to be less than 10% of the expected SM signal yield or less than 20% of the expected statistical uncertainty in the SM signal yield. Thus, a passing function must satisfy at least one of these modified spurious signal criteria:

- $N_{sp} < 10\% N_{s,exp}$
- $N_{sp} < 20\% \sigma_{s,exp}$

When two or more functions satisfy those requirements, the background model with the least degree of freedom is chosen.

The spurious signal method can be modified to accommodate categories whose MC background templates have large statistical uncertainties compared to the expected. To account for this effect, the error associated with the local statistical uncertainty of the MC template $\Delta_{MC}(N_s)$ is considered. To test whether N_s is statistically compatible with the maximum allowed value, a new metric ζ_s is defined:

$$\zeta_s(m_{\gamma\gamma}) = \begin{cases} N_s + 2\Delta_{MC}, & N_s + 2\Delta_{MC} < 0 \\ N_s - 2\Delta_{MC}, & N_s - 2\Delta_{MC} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (4.9)$$

In other words, the spurious signal is relaxed to accommodate 2σ local fluctuations in the MC template.

The maximum ζ_s in the range $121 < m_{\gamma\gamma} < 129$ GeV is taken as the spurious signal, denoted ζ_{SP} . The criteria is the same as before.

- $\zeta_{sp} < 10\% N_{s,exp}$
- $\zeta_{sp} < 20\% \sigma_{s,exp}$

The new method is designed to prevent functions from being excluded in the case of statistically-limited MC templates. The systematic uncertainty associated with the spurious signal is unchanged; it is still N_{sp} measured for a given function.

A second function choice scenario was considered in which the passing function with the smallest total uncertainty is selected in each category (total uncertainty here is defined as the statistical uncertainty of the signal yield estimate at $m_h = 125$ GeV added in quadrature with the spurious signal systematic uncertainty).

Table 4.10 shows the selected functions in each category, its associated systematic uncertainties on the signal amplitudes expressed in the size of the spurious signal N_{spur} , its size relative to the expected statistical error on the signal measurement Z_{spur} , and its ratio to the predicted number of signal events μ_{spur} .

Category	Model	N_{spur}	Z_{spur} [%]	μ_{spur} (syst) [%]
ggH_0J_Cen	ExpPoly2	-26.5	-29.4	-7.95
ggH_0J_Fwd	ExpPoly2	-46.0	-24.4	-7.96
ggH_1J_LOW	ExpPoly2	32.2	29.3	11.1
ggH_1J_MED	ExpPoly2	8.69	13.1	5.54
ggH_1J_HIGH	Pow	-3.61	-21.6	-11.5
ggH_1J_BSM	Exponential	1.32	43.9	59.7
ggH_2J_LOW	ExpPoly2	-13.9	-21.2	-17.1
ggH_2J_MED	ExpPoly2	7.78	16.0	10.7
ggH_2J_HIGH	Pow	3.64	18.9	12.7
ggH_2J_BSM	Pow	2.02	-36.8	-27.2
VBF_HjjLOW_loose	Exponential	3.94	31.2	20.2
VBF_HjjLOW_tight	Exponential	0.417	10.7	2.99
VBF_HjjHIGH_loose	Exponential	-2.33	-12.8	-14.0
VBF_HjjHIGH_tight	Exponential	2.28	18.8	11.3
VHhad_loose	Exponential	3.32	18.8	20.1
VHhad_tight	Exponential	2.27	27.7	18.5
qqH_BSM	Exponential	7.14	37.3	26.7
VHMET_LOW	Exponential	-0.497	-24.1	-81.1
VHMET_HIGH	Exponential	0.559	26.6	43.5
VHlep_LOW	Exponential	-1.90	-26.3	-29.7
VHlep_HIGH	Exponential	0.427	25.6	28.6
VHdilep	Pow	-0.176	-18.0	-19.1
tHhad 4j2b	Pow	-0.037	-1.38	-6.52
tHhad 4j1b	Pow	-0.25	-3.47	-9.73
ttHhad BDT4	Exponential	0.38	10.1	15.4
ttHhad BDT3	Exponential	0.057	3.72	9.72
ttHhad BDT2	Exponential	0.082	4.55	4.77
ttHhad BDT1	Exponential	0.053	3.57	3.75
ttHlep	Pow	-0.25	-16.2	-10.7
tHlep 1fwd	Pow	-0.29	-19.6	-26.2
tHlep 0fwd	Pow	0.29	12.9	28.5

Table. 4.10: Spurious signal results for the reconstructed categories. In each category, the function chosen to model the background distribution of $m_{\gamma\gamma}$ is listed, along with the associated systematic uncertainties on the signal amplitudes expressed in the size of the spurious signal (N_{spur}), its size relative to the expected statistical error on the signal measurement (Z_{spur}), and its ratio to the predicted number of signal events (μ_{spur}). The “Pow” refers to the first-order Power Law; and the “Exponential” and “ExpPoly2” models are exponentials of first- and second-order polynomials.

4.7 Statistical model

4.7.1 Parameters of interest

Parameters of interest (POIs) are the parameters we would like to measure, e.g. inclusive signal strength, cross section of different production modes, or coupling modifiers. Different set of POIs (parameterizations) are used to interpret the data in order to reveal different physics information.

4.7.2 Nuisance Parameters

The fit model includes nuisance parameters (NPs), which are floated in the fit but are not of interest for the Higgs boson measurements. Some of these parameters are determined only from data, and are referred to as unconstrained. Other parameters are also constrained using information from auxiliary measurements, in addition to the data. These parameters are referred to as constrained and quantify the effect of systematic uncertainties in the measurement.

The auxiliary measurements are always assumed to be expressible as independent unit-Gaussian constraints for each constrained NP. When the same systematic uncertainty source affect both channels, the corresponding nuisance parameters will be equated between them. The mean of the Gaussian is the global observable representing the observed value of the auxiliary measurement [80].

4.7.3 Measurement Likelihood

The statistical methods used in this chapter follow those of Ref. [81] and Ref. [82]. In order to build an extended likelihood function, analytic functions of the number of observed events and the corresponding diphoton mass are used to describe the distributions of $m_{\gamma\gamma}$ in the range 105–160 GeV for the signal and the background.

The likelihood for a given reconstructed category is a Poisson probability distribution,

$$\mathcal{L}_i = \text{Pois}(n_i | N_i(\boldsymbol{\theta})) \cdot \prod_{j=1}^{n_i} f_i(m_{\gamma\gamma}^j, \boldsymbol{\theta}) \cdot G(\boldsymbol{\theta}, \tilde{\boldsymbol{\theta}}),$$

where n_i and N_i are the observed and expected number of selected candidates. $f_i(m_{\gamma\gamma}^j)$ stands for the value of the probability density function of the invariant mass distribution evaluated for each candidate j , $\boldsymbol{\theta}$ are nuisance parameters, $\tilde{\boldsymbol{\theta}}$ are the global observables corresponding to $\boldsymbol{\theta}$, and $G(\boldsymbol{\theta})$ the constraint term, defined as a set of unit Gaussian constraints on a subset of the nuisance parameters. In order to get the likelihood for the measurements of the total Higgs boson production-

mode cross sections and signal strengths, the likelihood functions of each event reconstruction category are multiplied together.

The number of expected candidates consists of the signal and background yields, denoted by N_i^{sig} and N_i^{bkg} , and the spurious signal yield described in Section 4.6, $N_i^{\text{spur}} \cdot \theta_{\text{spur},c}$,

$$N_i = N_i^{\text{sig}} + N_i^{\text{bkg}} + N_i^{\text{spur}} \cdot \theta_{\text{spur},c}.$$

For the nominal systematic uncertainties giving both up and down impact, a Gaussian factor

$$F_G(\sigma, \theta) = (1 + \sigma \cdot \theta)$$

is incorporated into the likelihood function.

for the effect of an uncertainty that a negative model parameter does not make physical sense, a log-normal pdf is injected.

$$F_{\text{LN}}(\sigma, \theta) = e^{\sqrt{\ln(1+\sigma^2)}\theta}$$

By using the same nuisance parameter, two uncertainties are fully correlated when the source are exactly the same. Partially-correlated uncertainties are decomposed into uncorrelated and correlated nuisance parameters.

A profile likelihood ratio test statistic is used to determine the measured Higgs boson signal yields,

$$\Lambda(\nu) = -2 \ln \frac{\mathcal{L}(\nu, \hat{\boldsymbol{\theta}}_\nu)}{\mathcal{L}(\hat{\nu}, \hat{\boldsymbol{\theta}})}, \quad (4.10)$$

where ν and $\boldsymbol{\theta}$ are the parameters of interest and the nuisance parameters, respectively. In the numerator, the nuisance parameters are set to their profiled values $\hat{\boldsymbol{\theta}}_\nu$, which maximize the likelihood function for fixed values of the parameters of interest ν . In the denominator, both the parameters of interest and the nuisance parameters are set to the values $\hat{\nu}$ and $\hat{\boldsymbol{\theta}}$ respectively which jointly maximize the likelihood.

In the asymptotic approximation, in which the likelihood is approximately Gaussian, $\Lambda(\nu)$ may be interpreted as an increase in χ^2 from its minimum value [81] to derive the approximate confidence intervals.

When $\Lambda(\nu) = 1$ with all other parameters “profiled” (i.e. set to the values that maximize the likelihood for those values of ν), the total uncertainty in ν can be obtained. In addition, by fixing different groups of uncertainties to their unconditional fit value, error decomposition can be performed. Statistical uncertainty can be determined by fixing all nuisance parameters to their best-fit values, except for those describing the background shape and normalization. The

theoretical (experimental) uncertainty is found by subtracting in quadrature the experimental (theoretical) uncertainties and the statistical uncertainties from the total uncertainty.

4.8 Systematic uncertainties

Systematic uncertainties can be divided into two general types, which are briefly summarized below and discussed in the following part of this section.

- Theoretical uncertainties include uncertainties on the QCD scale, parton density functions, the strong coupling constant, and branching ratios. Theoretical uncertainties can impact the modelling of observables of a given signal process topology, affecting the signal yield and migrations between STXS truth bins. They also include uncertainties from an imperfect parton shower model and from the description of the underlying event. The Standard Model cross-section and branching ratio predictions are used as the reference for the signal strength (μ) measurements, and the theoretical uncertainties affecting the total predicted SM yield are reflected in the μ measurements. The cross-section times branching ratio measurements reported in the context of the STXS framework, either inclusively or per production mode, do not use the Standard Model as a reference. As such, the theoretical uncertainties affecting the cross-section measurements are restricted to acceptance and migration uncertainties. These acceptance and migration uncertainties do depend on the merging of STXS bins and are evaluated independently for the STXS and production cross-section measurements.
- Experimental uncertainties include sources such as the luminosity measurement; object reconstruction, identification and trigger efficiencies; object energy scale and resolution; the modeling of pile-up; and the primary vertex selection efficiency. Most of the experimental sources of uncertainty affect the inclusive signal yields or cause migrations between categories. There are two special groups of uncertainties associated with the parameterization of the signal and background when fitting the $m_{\gamma\gamma}$ spectrum. The first is the photon energy scale and resolution experimental uncertainties affect the $m_{\gamma\gamma}$ distribution of the signal resonance. The group of uncertainties corresponding to the background modelling, is evaluated by measuring the amount of spurious signal measured in a simulated background-only sample as defined in Section 4.6.2.

Table 4.11 summarizes the implementation of systematic uncertainties in the statistical model. The impact of the uncertainties on the measurement can be found in Sections 4.9.2.

Systematic uncertainty source		N_{NP}	Constraint	
Theory	ggF QCD	9	$N_{\text{S}}^{\text{ggF}} F_{\text{LN}}(\sigma_i, \theta_i)$	
	Missing higher orders (non-ggF)	6	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	
	$B(H \rightarrow \gamma\gamma)$	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$	
	PDF	30	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	
	α_{S}	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	
	UE/PS	5	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	
Experimental	Yield	Heavy flavor content	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Luminosity	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Trigger	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Photon identification	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Photon isolation	2	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
	Migration	Flavor tagging	14	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Jet	20	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Jet flavor composition	7	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Jet flavor response	7	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Electron	3	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Muon	11	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Missing transverse momentum	3	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Pileup	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
		Photon energy scale	40	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$
Mass	ATLAS-CMS m_h		1	$\mu_{\text{CB}} F_{\text{G}}(\sigma_i, \theta_i)$
	Photon energy scale		40	$\mu_{\text{CB}} F_{\text{G}}(\sigma_i, \theta_i)$
	Photon energy resolution		9	$\sigma_{\text{CB}} F_{\text{LN}}(\sigma_i, \theta_i)$
Background	Spurious signal	Varies	$N_{\text{spur},c} \theta_{\text{spur},c}$	

Table. 4.11: Summary of the sources of systematic uncertainties for results based on event reconstruction categories.

4.8.1 Experimental systematic uncertainties

The experimental uncertainties affecting the expected overall signal yield and causing migrations of events between categories are listed here.

The sources of uncertainties in the expected signal yield:

- The luminosity delivered to the ATLAS experiment. The uncertainty in the combined 2015+2016 integrated luminosity is 3.2%. It is derived from a calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016 [83].
- The the diphoton trigger efficiency. A 0.4% uncertainty is estimated by using a bootstrap method [22] to compare the trigger efficiencies in data and simulation.
- The photon identification efficiency. Its uncertainty is computed by varying the identification efficiency scale factors within their uncertainties measured from radiative Z boson decays and from inclusive γ events, and of electrons from $Z \rightarrow e^+ e^-$ decays. It is estimated to be 1.6%.
- The photon track isolation efficiency. By measuring the track isolation cut efficiency of the inclusive photon samples, its uncertainty is estimated to be 0.8%.
- The photon calorimeter isolation efficiency. Its uncertainty is estimated to be 0.1% and is obtained from comparison of efficiency between turning on and off corrections of simulated inclusive photon events on the calorimeter isolation variable.

Uncertainties causing migrations between categories and bins include:

- The modeling of pileup in the simulation. This uncertainty is around 1.4 - 5.6% for different categories. The number is obtained by varying the average number of pileup events in the simulation by an amount consistent with data.
- Uncertainties in the photon energy scale and resolution. These uncertainties cause migrations between the event reconstruction categories and impact the expected number of events. $Z \rightarrow e^+ e^-$ simulation samples are used to make this calibration. A p_T -dependent uncertainty impact is obtained between 0.2% for events with a low diphoton p_T up to 1.9% for high diphoton p_T events.
- Uncertainties in the jet energy calibration and the jet energy resolution. Uncertainties from 2.8% to 15% are derived from varying the jet energies by an amount commensurate with the differences observed between 13 TeV

data and simulation in the transverse momentum balance in dijet, $\gamma + \text{jet}$ and $Z + \text{jet}$ events [35, 84].

- Uncertainties due to the efficiency of the jet vertex tagger. By applying the simulation corrections shifted with an amount allowed by the data, these uncertainties are obtained.
- b -tagging algorithm. top-quark related categories are affected by uncertainties corresponding to the b -tagging algorithm.
- Electron [85] and muon [32] reconstruction, identification and isolation efficiencies. A tag-and probe technique is used in dilepton decays of Z bosons and J/ψ mesons collected in Run 2, resulting in about 0.6% for electrons uncertainties and about 0.5% for muons uncertainties.
- Electron [86] and muon [32] resolution, energy and momentum scale. Those uncertainties are determined from comparisons between the reconstructed invariant mass in data and simulation of dileptons from decays of Z bosons or J/ψ mesons, which is determined to be negligible for all measurements.
- The E_T^{miss} uncertainty. The source is both the E_T^{miss} itself and the hard objects. A typical migration uncertainties ranging from 4.0% to 4.8% for relevant categories is obtained.

Another part of uncertainties are the the photon energy scale and resolution affecting the signal modeling, and the uncertainties due to the specific choice of background model.

The Higgs boson mass $m_H = 125.09 \pm 0.24 \text{ GeV}$ [87] is fixed in the signal strength extraction. An uncertainty in the signal peak position 0.24 GeV is added as a nuisance parameter in the fit. The uncertainty in the Higgs boson mass is dominated by the statistical component, and the muon momentum and electromagnetic energy scale uncertainties from the ATLAS and CMS experiment. This nuisance parameter is found to impact the measured inclusive signal strength by less than $\pm 0.1\%$.

The photon energy scale can shift the position of the peak, and the photon energy resolution can broaden or narrow the signal peak, which will impact the signal model. Those are typically among the dominant sources of systematic uncertainty in the measurement. The determination of those systematic uncertainties in the photon energy resolution and scale follows Refs. [28, 88], deriving the overall energy scale factors and their uncertainties based on $Z \rightarrow e^+e^-$ events collected during 2015 and 2016. The photon energy scale uncertainties can give impact to the peak position by between $\pm 0.21\%$ and $\pm 0.36\%$ of the nominal peak position. The width of the signal distribution can be changed by between

$\pm 6\%$ and $\pm 13\%$ of the nominal width by the photon energy resolution uncertainty. The size of both uncertainties is dependent on the energy, rapidity and jet activity of the selected photon pair.

The uncertainty due to the choice of background function is expressed as a systematic on the number of fitted signal events, and taken to be uncorrelated across categories. The spurious signal method is used to fit the $m_{\gamma\gamma}$ spectrum reconstructed from background-only simulated samples, as discussed in Section 4.6.

4.8.2 Theoretical and modeling uncertainties

The signal strength measurements, which are ratios of the observed to predicted event yields are affected by the overall theoretical cross-section uncertainties. The cross-section measurements won't be impacted as they do not rely on absolute predictions.

The theoretical modeling uncertainties in the per-category acceptance of each production process affect the measurement of production-mode cross sections and signal strengths. The parton distribution functions (PDFs) and the α_s uncertainties are estimated using the PDF4LHC15 recommendations [89]. For the gluon-gluon fusion process, the total production-mode cross section uncertainty is 3.9%, calculated at N³LO precision in QCD, as determined by QCD-scale variations and including top, bottom, and charm quark mass effect uncertainties. When requiring additional jets or high Higgs boson p_T , the perturbative uncertainty becomes significantly larger in different kinematic regions. Nine uncertainty sources are included to take this effect into account:

- The jet multiplicities due to missing higher-order corrections uncertainties are taken into account by using the STWZ [90] and BLPTW [90, 91] predictions as an input. The yield uncertainties are up to 8.9% in each STXS region. And migration uncertainties are up to 18% in each STXS region.
- the Higgs boson p_T uncertainty can be divided into three systematics, including two represent the migration uncertainty between the intermediate and high p_T region with events with at least one jet, and a uncertainty parameterizes the missing higher-order correction of top-quark mass effects in the gluon-gluon fusion loop. It mainly impacts events at $p_T > 500$ GeV.
- The gluon-gluon fusion events migrate to the VBF categories due to missing QCD higher-orders in the calculation. Those uncertainties are estimated by variations of the renormalization and factorization scales in MCFM by a factor of two around the nominal scale of $\mu_r = \mu_f = m_h$. The uncertainty is between 20% and 32%.

In the $t\bar{t}H$ and tH categories, an uncertainty of 100% is assigned to the normalization of the ggF, VBF, and VH production mechanisms.

The “UE/PS” uncertainty, which is the modeling of the parton shower, underlying event and hadronization affects all measurements. It is estimated by switching the parton showering algorithm from Pythia8 to Herwig7 in the ggF, VBF, and VH samples and from Herwig++ to Pythia8 in the $t\bar{t}H$ sample. The relative difference in acceptance at particle level is taken as the uncertainty under each production modes. A eigenvector tune effect of ggF from the AZNLO set provides an additional uncertainty.

The normalization uncertainty from the $H \rightarrow \gamma\gamma$ branching ratio is taken from HDECAY and PROPHECY4F.

4.9 Results

This results of the total and production mode specific signal strength measurements, the total production cross sections and simplified template cross sections and the coupling-strength fits are discussed in this section.

4.9.1 Data distributions

Figure 4.30 shows the weighted inclusive observed diphoton invariant mass spectrum. Figure 4.31 shows the weighted invariant mass distributions for the sums of the categories targeting the different production modes. Two set of signal strength numbers are extracted from fitting. The inclusive signal strength is obtained from a fit of Figure 4.30, which will affect simultaneously all production modes. In the fits of Figure 4.31, the four signal strengths μ_{ggF} , μ_{VBF} , μ_{VH} and $\mu_{\text{t}\bar{\text{t}}\text{H}+\text{tH}}$ are allowed to vary separately. As discussed in Section 4.6, the Higgs boson mass is set to $m_h = 125.09 \pm 0.24$ GeV.

4.9.2 Signal strengths

The signal strengths are measured with the extended likelihood analysis (Section 4.7).

The inclusive signal strength μ definition includes all resonant signal processes with associated theoretical uncertainties on the cross-section and branching ratio. The negative log-likelihood scan of the inclusive signal strength is shown in Figure 4.32.

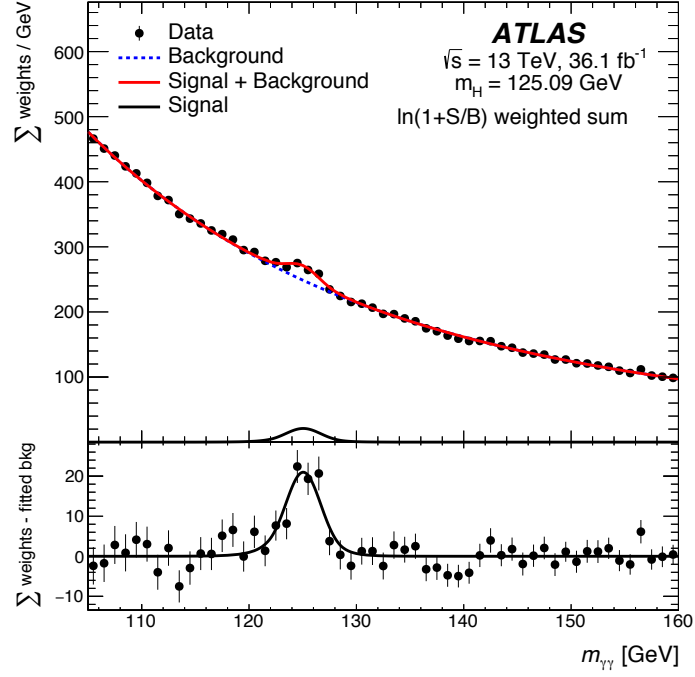
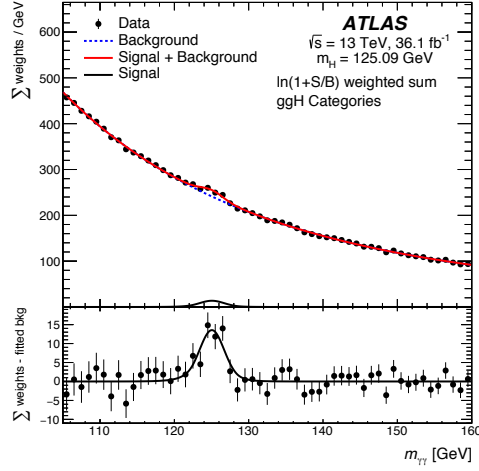
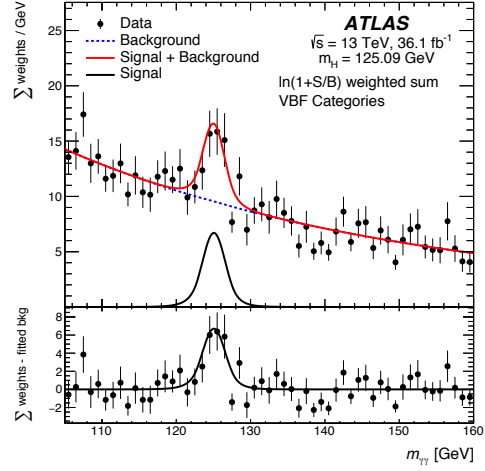


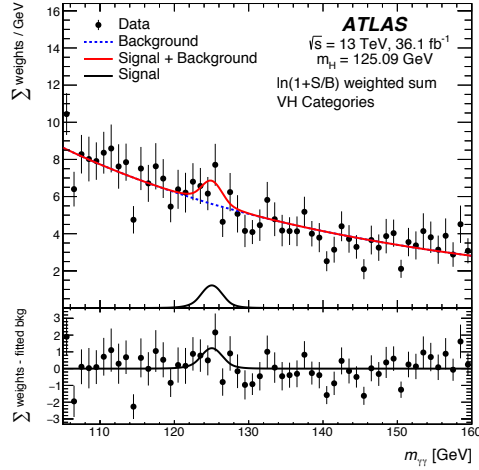
Fig. 4.30: Weighted diphoton invariant mass spectrum for the sum of all categories observed at 13 TeV in the 2015 and 2016 data. Events are weighted by $\ln(1 + S_{90}/B_{90})$, where (S_{90}/B_{90}) for each category is the expected signal (background) in the smallest $m_{\gamma\gamma}$ window containing 90% of the expected signal. The fitted signal-plus-background model is shown with the solid red curve. The dotted blue curve is the background component, while solid black curve is the signal component of the fit. Both the signal-plus-background and background-only curves reported here are obtained from the weighted sum of the individual curves in each category. The residuals between the data and the background component of the fitted model are shown in the bottom panel. In fits, the Higgs boson mass is constrained to be $125.09 \pm 0.24 \text{ GeV}$.



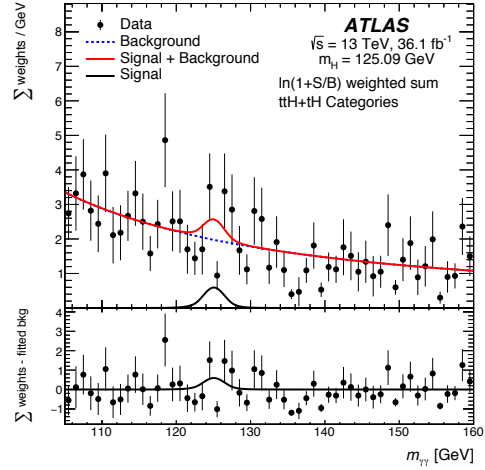
(a) “untagged” categories and the “jet BSM” category, in which the expected signal is produced mainly through gluon–gluon fusion



(b) VBF categories



(c) VH categories



(d) $t\bar{t}H$ categories

Fig. 4.31: Weighted diphoton invariant mass spectra for events for the sum of corresponding categories observed at 13 TeV in the 2015 and 2016 data. Events are weighted by $\ln(1 + S_{90}/B_{90})$, where (S_{90}/B_{90}) for each category is the expected signal (background) in the smallest $m_{\gamma\gamma}$ window containing 90% of the expected signal. The fitted signal-plus-background model is shown with the solid red curve. The dotted blue curve is the background component, while solid black curve is the signal component of the fit. Both the signal-plus-background and background-only curves reported here are obtained from the weighted sum of the individual curves in each category. The residuals between the data and the background component of the fitted model are shown in the bottom panel. In fits, the Higgs boson mass is constrained to be 125.09 ± 0.24 GeV.

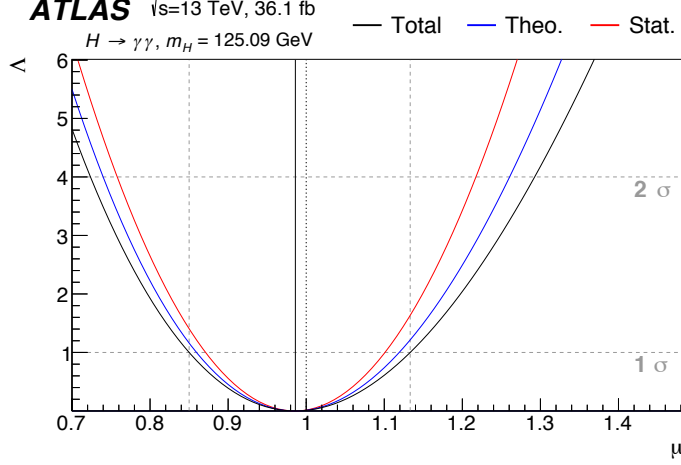


Fig. 4.32: Negative log-profile likelihood Λ as a function of the observed inclusive signal strength μ with all systematic uncertainties included (black line), with parameters describing experimental uncertainties fixed to their best-fit values (blue line), with the same procedure applied to all systematic uncertainties (red line).

The measured central value and 68% CL interval for the inclusive signal strength is:

$$\mu = 0.99^{+0.15}_{-0.14} = 0.99 \pm 0.12 \text{ (stat.) }^{+0.06}_{-0.05} \text{ (exp.) }^{+0.07}_{-0.05} \text{ (theo.)} ,$$

A relatively good agreement is found comparing to the SM prediction.

When comparing this result to the ATLAS Run-1 diphoton signal strength measurement of $\mu = 1.17 \pm 0.23 \text{ (stat.) }^{+0.10}_{-0.08} \text{ (exp.) }^{+0.12}_{-0.08} \text{ (theo.)}$, around a factor of two improvement is obtained in each component of the uncertainty.

The impact of the main sources of systematic uncertainty presented in Table 4.11 on the measured inclusive signal strength are presented in Table 4.12.

The signal strength of the four measured production modes are measured by varying them independently during the fit. The definition of ZH includes the gluon initiated production and $b\bar{b}H$ shares a common signal strength with ggF. The results of these fits are shown below as well as summarized in Figure 4.33.

$$\begin{aligned} \mu_{\text{ggF}} &= 0.81^{+0.19}_{-0.18} = 0.81 \pm 0.16 \text{ (stat.) }^{+0.07}_{-0.06} \text{ (exp.) }^{+0.07}_{-0.05} \text{ (theo.)} \\ \mu_{\text{VBF}} &= 2.0^{+0.6}_{-0.5} = 2.0 \pm 0.5 \text{ (stat.) }^{+0.3}_{-0.2} \text{ (exp.) }^{+0.3}_{-0.2} \text{ (theo.)} \\ \mu_{\text{VH}} &= 0.7^{+0.9}_{-0.8} = 0.7 \pm 0.8 \text{ (stat.) }^{+0.2}_{-0.2} \text{ (exp.) }^{+0.2}_{-0.1} \text{ (theo.)} \\ \mu_{\text{top}} &= 0.5^{+0.6}_{-0.6} = 0.5^{+0.6}_{-0.5} \text{ (stat.) }^{+0.1}_{-0.1} \text{ (exp.) }^{+0.1}_{-0.0} \text{ (theo.)} \end{aligned}$$

It is assumed $\mu_{\text{VH}} = \mu_{\text{ZH}} = \mu_{\text{WH}}$ due to the lack of statistic to probe Higgs

Uncertainty Group	$\sigma_{\mu}^{\text{syst.}}$
Theory (QCD)	0.041
Theory ($B(H \rightarrow \gamma\gamma)$)	0.028
Theory (PDF+ α_S)	0.021
Theory (UE/PS)	0.026
Luminosity	0.031
Experimental (yield)	0.017
Experimental (migrations)	0.015
Mass resolution	0.029
Mass scale	0.006
Background shape	0.027

Table. 4.12: Main systematic uncertainties $\sigma_{\mu}^{\text{syst.}}$ in the combined signal strength parameter μ . The values for each group of uncertainties are determined by subtracting in quadrature from the total uncertainty the change in the 68% CL range of μ when the corresponding nuisance parameters are fixed to their best fit values. The uncertainties correspond to the sources detailed in Table 4.11.

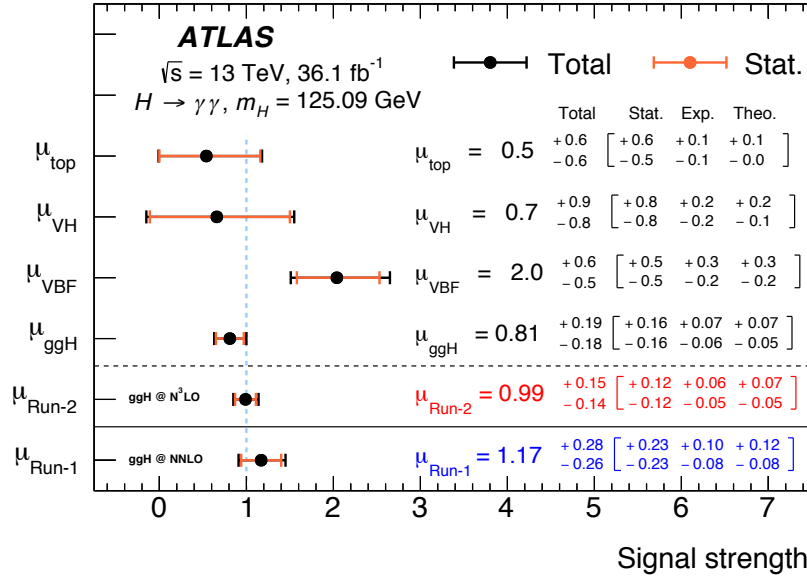


Fig. 4.33: Summary of the signal strength of production mode (ggF, VBF, VH and top) and the inclusive one ($\mu_{\text{Run-2}}$). The inclusive signal strength measured at 7 and 8 TeV is also listed as $\mu_{\text{Run-1}}$ [1].

boson production via VH . The $b\bar{b}H$ contributions are correlated with ggF (i.e. $\mu_{b\bar{b}H} = \mu_{\text{ggF}}$), as well as correlating the tH and $t\bar{t}H$ productions (i.e. $\mu_{\text{top}} = \mu_{t\bar{t}H+tH}$).

The VBF signal strength is found to be 2.2σ above the prediction. A 4.9σ significance is observed.

Table 4.13 summarizes the significance numbers for VBF VH and $t\bar{t}H+tH$ production modes.

Measurement	Expected Z_0	Observed Z_0
μ_{VBF}	2.6σ	4.9σ
μ_{VH}	1.4σ	0.8σ
μ_{top}	1.8σ	1.0σ

Table. 4.13: Expected and observed significances of the VBF, VH and top quark associated production mode signal strengths.

Process ($ y_H < 2.5$)	Result		Uncertainty [fb]			SM prediction [fb]
	[fb]	Total	Stat.	Exp.	Theo.	
ggF	82	$^{+19}_{-18}$	$\left(\pm 16 \right)$	$^{+7}_{-6}$	$^{+5}_{-4}$	102^{+5}_{-7}
VBF	16	$^{+5}_{-4}$	$\left(\pm 4 \right)$	± 2	$^{+3}_{-2}$	8.0 ± 0.2
VH	3	± 4	$\left(\begin{smallmatrix} +4 \\ -3 \end{smallmatrix} \right)$	± 1	$^{+1}_{-0}$	4.5 ± 0.2
Top	0.7	$^{+0.9}_{-0.7}$	$\left(\begin{smallmatrix} +0.8 \\ -0.7 \end{smallmatrix} \right)$	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.0}$	1.3 ± 0.1

Table. 4.14: Best-fit values and uncertainties of the production-mode cross sections times branching ratio.

4.9.3 Production-mode cross sections

Fits are performed to evaluate the production-mode cross sections for $m_H = 125.09 \pm 0.24$ GeV in a region with Higgs-boson rapidity $|y_H| < 2.5$, multiplied by the branching ratio of the Higgs boson decay to diphotons.

The SM predicted relative ratios between $t\bar{t}H$, tHq , and tHW production-mode cross sections are used to merge them to σ_{top} . The same assumption is also applied when the WH and ZH are merged into VH .

Only theoretical uncertainty in the acceptance come into fitting. The total uncertainty is found by profiling all nuisance parameters in the fit while the statistical uncertainty is found by fixing all constrained nuisance parameters to their best fit values. The continuum background normalization and shape parameters are unconstrained and remain profiled in all fits.

The production-mode cross sections are summarized in Figure 4.34 and Table 4.14.

The 68% and 95% CL two-dimensional contours of $\sigma_{\text{ggF}} \times B(H \rightarrow \gamma\gamma)$ and $\sigma_{\text{VBF}} \times B(H \rightarrow \gamma\gamma)$ are shown in Figure 4.35, with other production modes profiled.

A ratios of the production-mode cross sections to the ggF cross section measurement is performed to remove the impact of possible deviations in the $H \rightarrow \gamma\gamma$

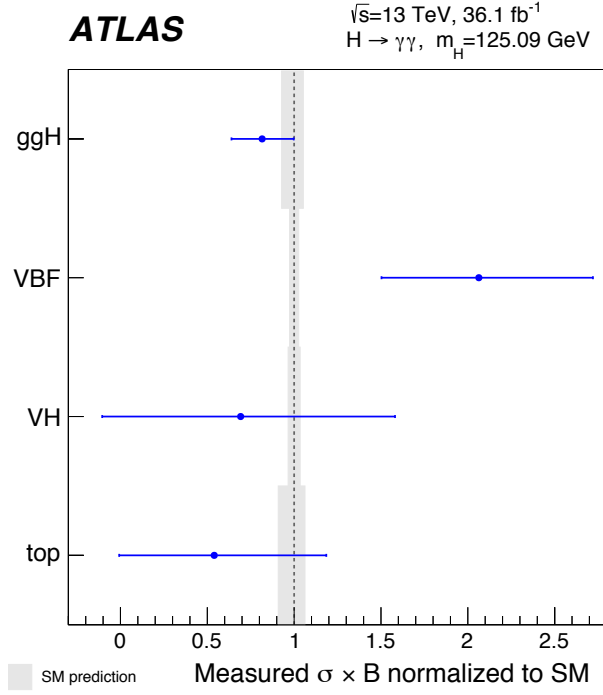


Fig. 4.34: Normalized-to-SM values of the measured production-mode cross sections times the Higgs diphoton decaying branching ratio.

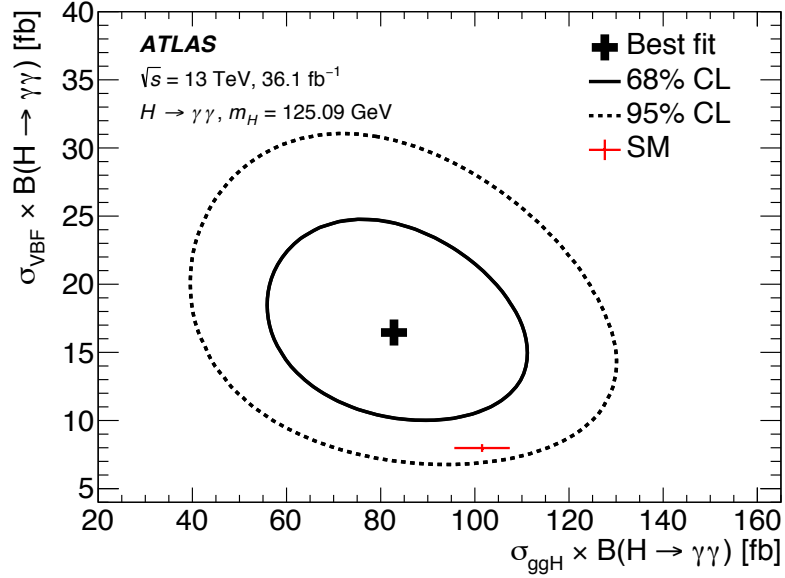


Fig. 4.35: Likelihood contours in the $(\sigma_{\text{ggF}} \times B(H \rightarrow \gamma\gamma), \sigma_{\text{VBF}} \times B(H \rightarrow \gamma\gamma))$ plane, compared to the Standard Model prediction (red cross) for a Higgs boson mass $m_h = 125.09\text{ GeV}$.

Process ($ y_H < 2.5$)	Result		Uncertainty			SM prediction
			Total	Stat.	Exp.	
$\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$	0.20	$+0.10$ -0.07	$\left(\begin{array}{ccc} +0.09 & +0.04 & +0.04 \\ -0.06 & -0.02 & -0.02 \end{array} \right)$			$0.078^{+0.005}_{-0.006}$
$\sigma_{\text{VH}}/\sigma_{\text{ggF}}$	0.04	$+0.06$ -0.05	$\left(\begin{array}{ccc} +0.06 & +0.01 & +0.01 \\ -0.04 & -0.01 & -0.01 \end{array} \right)$			$0.045^{+0.004}_{-0.005}$
$\sigma_{\text{top}}/\sigma_{\text{ggF}}$	0.009	$+0.010$ -0.009	$\left(\begin{array}{ccc} +0.010 & +0.002 & +0.002 \\ -0.009 & -0.001 & -0.001 \end{array} \right)$			$0.012^{+0.001}_{-0.002}$

Table. 4.15: Ratios of the production-mode cross sections with respect to the ggF cross section and uncertainties are shown. The SM predictions with their uncertainties are shown for each production process.

branching ratio. The normalized-to-SM prediction results are

$$\begin{aligned}
\frac{\sigma_{\text{VBF}}/\sigma_{\text{ggF}}}{(\sigma_{\text{VBF}}/\sigma_{\text{ggF}})^{\text{SM}}} &= 2.5^{+1.3}_{-0.9} = 2.5^{+1.1}_{-0.8} (\text{stat.})^{+0.5}_{-0.3} (\text{exp.})^{+0.5}_{-0.3} (\text{theo.}) \\
\frac{\sigma_{\text{VH}}/\sigma_{\text{ggF}}}{(\sigma_{\text{VH}}/\sigma_{\text{ggF}})^{\text{SM}}} &= 0.9^{+1.3}_{-1.0} = 0.9^{+1.2}_{-0.9} (\text{stat.})^{+0.3}_{-0.3} (\text{exp.})^{+0.2}_{-0.1} (\text{theo.}) \\
\frac{\sigma_{\text{top}}/\sigma_{\text{ggF}}}{(\sigma_{\text{top}}/\sigma_{\text{ggF}})^{\text{SM}}} &= 0.7^{+0.8}_{-0.7} = 0.7^{+0.8}_{-0.7} (\text{stat.})^{+0.2}_{-0.1} (\text{exp.})^{+0.2}_{-0.0} (\text{theo.})
\end{aligned}$$

The detailed absolute ratio numbers are also given in Table 4.15, with their statistical, experimental and theoretical uncertainties.

4.9.4 Simplified template cross sections

The STXS framework is designed to evolve alongside the growing ATLAS dataset. We are currently in the “Stage 1” phase of this design as described in Section 1.3. But due to the limited sensitivity to the cross section in some bins of the Stage 1 scheme, in particular due to limited data statistics in some regions, a merged version of the “Stage 1” simplified template cross-section measurements are investigated. There are in total ten regions merged from regions with poor sensitivity or with large anti-correlations: Six regions probe gluon-fusion Higgs boson production divided by jet multiplicity. Two regions defined to probe VBF production and Higgs boson production associated with hadronically-decay vector bosons. A dedicated cross section is measured for Higgs boson production associated with vector bosons that decay leptonically. One cross section measures top-associated ($t\bar{t}H$ and tH) Higgs-boson production. A ≥ 1 jet, $p_{\text{T}}^H > 200$ GeV gluon–gluon fusion and $p_{\text{T}}^j > 200$ GeV $qq' \rightarrow qq'H + q\bar{q} \rightarrow WH/ZH$ regions are left to retain sensitivity to beyond the Standard Model effect. Here p_{T}^H and p_{T}^j denote the Higgs boson and leading jet transverse momenta, respectively. However, due

to large anti-correlation between those two BSM-sensitive regions, only the cross section for the summed yield of these two regions is quoted here, and thus nine kinematic regions are finally reported.

In Table 4.16, the middle column summarizes the 10 probes, which are merged from the 31 stage-1 cross sections shown in the last column, including 11 ggH , 5 $qq' \rightarrow Hqq'$, 11 VH (leptonic decays), 3 Top-associated and 1 $b\bar{b}H$ production processes.

Process	Measurement region	Particle-level stage-1 region
$ggH + gg \rightarrow Z(\rightarrow qq)H$	0-jet	0-jet
	1-jet, $p_T^H < 60$ GeV	1-jet, $p_T^H < 60$ GeV
	1-jet, $60 \leq p_T^H < 120$ GeV	1-jet, $60 \leq p_T^H < 120$ GeV
	1-jet, $120 \leq p_T^H < 200$ GeV	1-jet, $120 \leq p_T^H < 200$ GeV
	≥ 1 -jet, $p_T^H > 200$ GeV	1-jet, $p_T^H > 200$ GeV
	≥ 2 -jet, $p_T^H < 200$ GeV or $qq' \rightarrow qq'H$ -like	≥ 2 -jet, $p_T^H > 200$ GeV
		≥ 2 -jet, $p_T^H < 60$ GeV
		≥ 2 -jet, $60 \leq p_T^H < 120$ GeV
		≥ 2 -jet, $120 \leq p_T^H < 200$ GeV
		$qq' \rightarrow qq'H$ -like, $p_T^{Hjj} < 25$ GeV
		$qq' \rightarrow qq'H$ -like, $p_T^{Hjj} \geq 25$ GeV
$qq' \rightarrow Hqq'$ (VBF + VH)	$p_T^j < 200$ GeV	$p_T^j < 200$ GeV, $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} < 25$ GeV
		$p_T^j < 200$ GeV, $qq' \rightarrow qq'H$ -like, $p_T^{Hjj} \geq 25$ GeV
		$p_T^j < 200$ GeV, $q\bar{q} \rightarrow WH/ZH$ -like
		$p_T^j < 200$ GeV, Rest
	$p_T^j > 200$ GeV	$p_T^j > 200$ GeV
VH (leptonic decays)	VH leptonic	$q\bar{q} \rightarrow ZH, p_T^Z < 150$ GeV
		$q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250$ GeV, 0-jet
		$q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250$ GeV, ≥ 1 -jet
		$q\bar{q} \rightarrow ZH, p_T^Z > 250$ GeV
		$q\bar{q} \rightarrow WH, p_T^W < 150$ GeV
		$q\bar{q} \rightarrow WH, 150 < p_T^W < 250$ GeV, 0-jet
		$q\bar{q} \rightarrow WH, 150 < p_T^W < 250$ GeV, ≥ 1 -jet
		$q\bar{q} \rightarrow WH, p_T^W > 250$ GeV
		$gg \rightarrow ZH, p_T^Z < 150$ GeV
		$gg \rightarrow ZH, p_T^Z > 150$ GeV, 0-jet
		$gg \rightarrow ZH, p_T^Z > 150$ GeV, ≥ 1 -jet
Top-associated production	top	$t\bar{t}H$ tHq and tHW
bbH	merged w/ ggH	bbH

Table. 4.16: Particle-level kinematic regions of the stage-1 simplified template cross sections measured in the analysis.

Measurement region ($ y_H < 2.5$)	Result	Uncertainty			SM prediction
		Total	Stat.	Syst.	
ggF, 0 jet	37	$^{+16}_{-15}$	$\left(\pm 14\right)$	$\left(^{+6}_{-5}\right)$ fb	63 ± 5 fb
ggF, 1 jet, $p_{\text{T}}^H < 60$ GeV	13	$^{+13}_{-12}$	$\left(\pm 12\right)$	$\left(^{+5}_{-4}\right)$ fb	15 ± 2 fb
ggF, 1 jet, $60 \leq p_{\text{T}}^H < 120$ GeV	5	± 6	$\left(\pm 6\right)$	$\left(^{+2}_{-1}\right)$ fb	10 ± 2 fb
ggF, 1 jet, $120 \leq p_{\text{T}}^H < 200$ GeV	2.8	$^{+1.7}_{-1.6}$	$\left(^{+1.6}_{-1.5}\right)$	$\left(^{+0.7}_{-0.5}\right)$ fb	1.7 ± 0.3 fb
ggF, ≥ 2 jet	20	$^{+9}_{-8}$	$\left(\pm 8\right)$	$\left(^{+4}_{-3}\right)$ fb	11 ± 2 fb
$qq \rightarrow Hqq, p_{\text{T}}^j < 200$ GeV	15	$^{+6}_{-5}$	$\left(\pm 5\right)$	$\left(^{+3}_{-2}\right)$ fb	10 ± 0.5 fb
ggF + $qq \rightarrow Hqq$, BSM – like	2.0	± 1.4	$\left(\pm 1.3\right)$	$\left(\pm 0.6\right)$ fb	1.8 ± 0.4 fb
VH, leptonic	0.7	$^{+1.4}_{-1.3}$	$\left(^{+1.4}_{-1.2}\right)$	$\left(^{+0.4}_{-0.3}\right)$ fb	1.4 ± 0.1 fb
Top	0.7	$^{+0.8}_{-0.7}$	$\left(^{+0.8}_{-0.7}\right)$	$\left(^{+0.2}_{-0.1}\right)$ fb	1.3 ± 0.1 fb

Table. 4.17: Best-fit values and uncertainties of the simplified template cross sections times branching ratio.

The evaluated cross sections including their correlations are summarized in Figures 4.36 and 4.37. The observed cross sections are all compatible with the SM prediction within 2σ confidence interval.

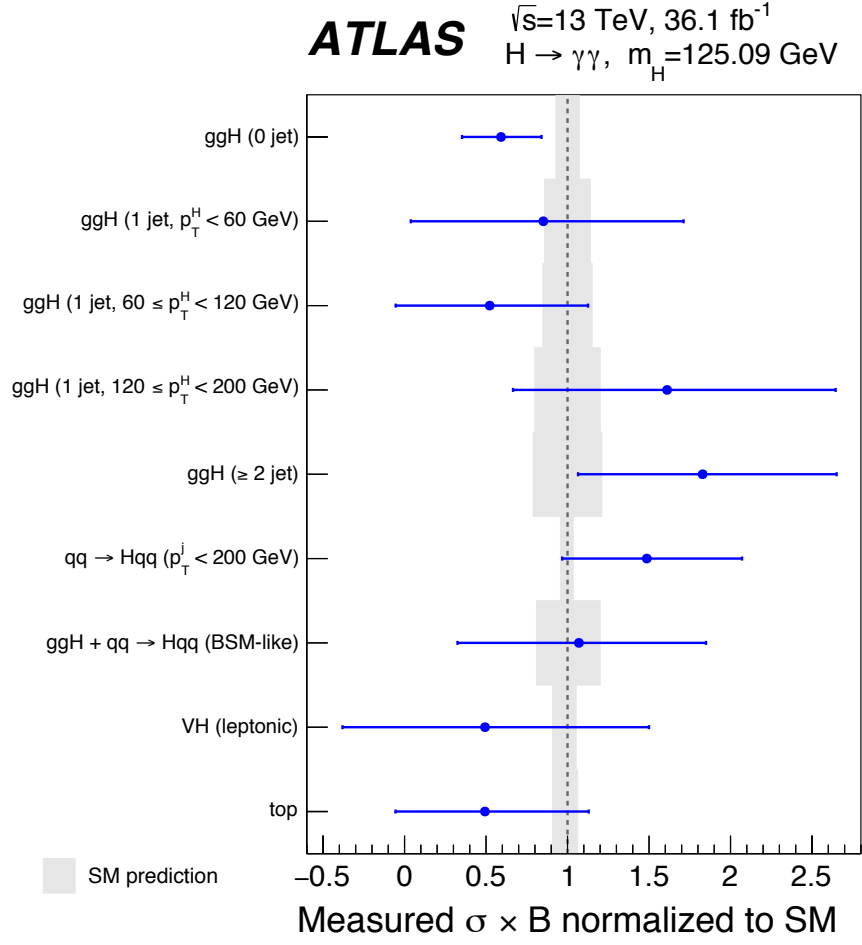


Fig. 4.36: Normalized-to-SM values of the measured STXS results. The theoretical uncertainties in the SM predictions are shown in gray in the plot.

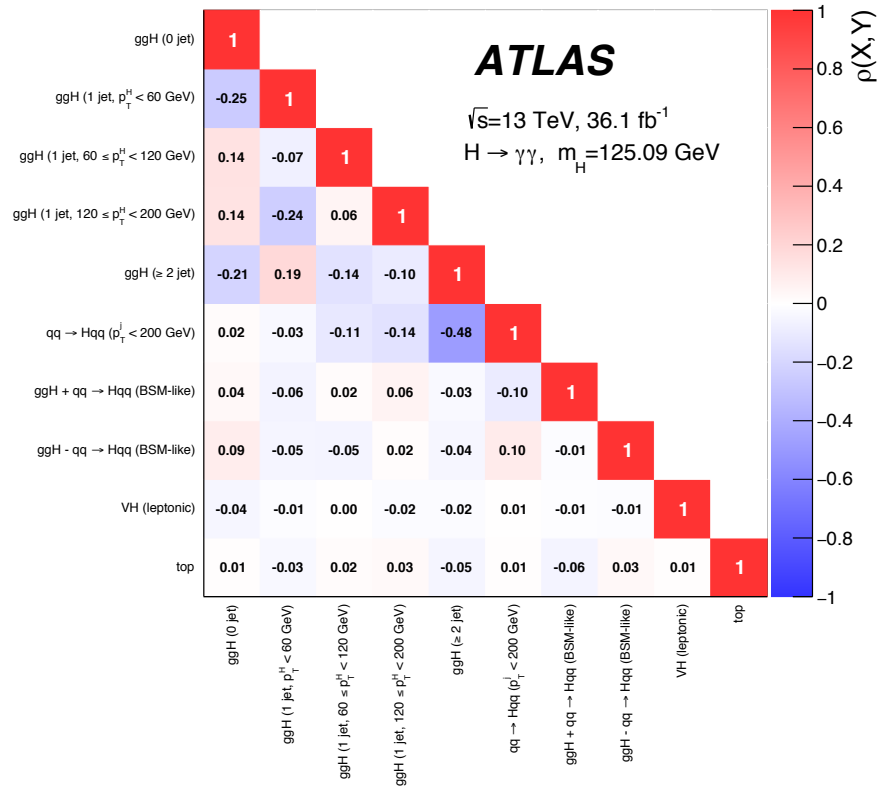


Fig. 4.37: Observed correlations between the measured simplified template cross sections, including both the statistical and systematic uncertainties.

4.9.5 Coupling-strength fits

Following the tree-level-motivated framework and benchmark models (Ref. [2], Section 1.4), measurements of Higgs boson coupling-strength modifiers κ_j are performed. In this single channel $H \rightarrow \gamma\gamma$ analysis, simple κ models are implemented.

In the first model, the effective coupling strengths to photons and gluons in loops κ_γ and κ_g are measured with the assumption that all other couplings are as in the SM. The best fit values and uncertainties are $\kappa_g = 0.76^{+0.17}_{-0.14}$ and $\kappa_\gamma = 1.16^{+0.14}_{-0.14}$.

In the second model, the universal coupling strength scale factors are measured: $\kappa_V = \kappa_W = \kappa_Z$ for all vector bosons and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$ for all fermions. The effective couplings corresponding to the ggH and $H \rightarrow \gamma\gamma$ vertex loops are resolved in terms of the fundamental SM couplings. The best fit values and uncertainties are $\kappa_F = 0.64^{+0.18}_{-0.14}$ and $\kappa_V = 0.92^{+0.08}_{-0.07}$.

Figure 4.38 shows the 68% and 95% CL two-dimensional contours of the two models. The SM prediction is found to be within the 68% CL contour for the first model and within the 95% CL contour for the second model.

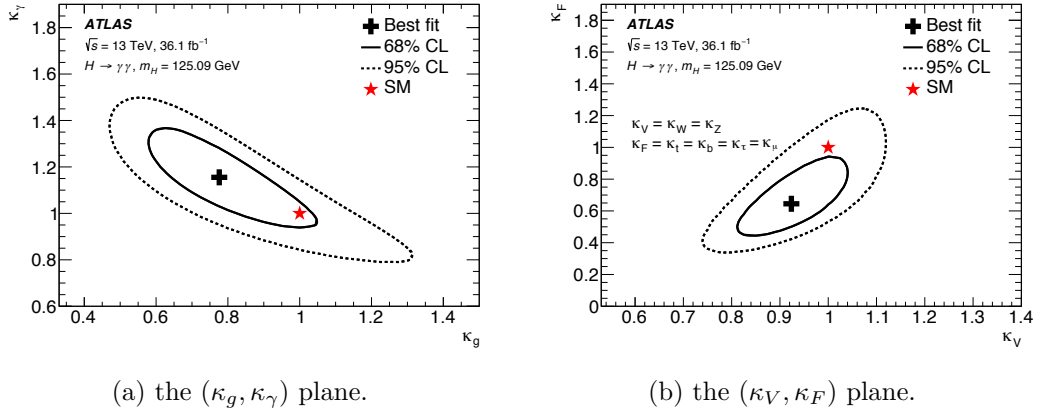


Fig. 4.38: Likelihood contours in two coupling-strength modifiers' plain. The Standard Model predictions are shown as the red stars.

4.10 Summary and the updated results

By using 36.1 fb^{-1} of proton–proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and collected by the ATLAS detector, measurements of Higgs boson production cross sections and couplings in the diphoton decay channel have been performed. All measurements assume a Higgs boson mass of $125.09 \pm 0.24 \text{ GeV}$.

The inclusive signal strength is determined to be

$$\mu = 0.99^{+0.15}_{-0.14} = 0.99 \pm 0.12 (\text{stat.})^{+0.06}_{-0.05} (\text{exp.})^{+0.07}_{-0.05} (\text{theo.}) .$$

Signal strengths of the main production modes are also reported. They are found to be:

$$\begin{aligned}\mu_{\text{ggF}} &= 0.81^{+0.19}_{-0.18}, \\ \mu_{\text{VBF}} &= 2.0^{+0.6}_{-0.5}, \\ \mu_{\text{VH}} &= 0.7^{+0.9}_{-0.8}, \\ \mu_{\text{top}} &= 0.5^{+0.6}_{-0.6}.\end{aligned}$$

A factor of two improvement is observed for the inclusive signal strength measurement comparing to the Run 1 ATLAS measurement in the diphoton channel [92]. The VBF signal strength is measured to be 2σ above the Standard Model expectation. The precision of the coupling-strength measurements involving top quarks improves by about a factor of three.

The cross sections of production modes including the gluon–gluon fusion, vector-boson fusion, and Higgs boson production in association with vector bosons or a top quark pair are reported. The parameter of interest studied are all in good agreements with the Standard Model predictions.

Stage-1 Higgs boson Simplified Template Cross Sections in many phase space regions are measured in a model-dependent way by using the strong-merged scheme. The results are comparable with theory predictions and no significant deviation from Standard Model expectations is observed.

Two parameterizations of Higgs boson coupling-strength modifiers are measured. Both the results on effective coupling-strength modifiers for Higgs boson production in gluon–gluon fusion and decay, κ_g and κ_γ , and the fermionic and vector boson couplings are close to the Standard Model prediction.

With the 79.8 fb^{-1} of proton–proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and recorded by the ATLAS detector in 2015–2017, the $H \rightarrow \gamma\gamma$ analysis [93] updated the results in $H \rightarrow \gamma\gamma$ channel. The most significant change

is that seven categories are updated to select $t\bar{t}H$ production, including both leptonic and hadronic top decay processes. The other categorization selections targeting the ggF VBF and VH production modes and the analysis strategy stay the same.

The updated inclusive signal strength is

$$\mu = 1.06^{+0.14}_{-0.12} = 1.06 \pm 0.08 \text{ (stat.) }^{+0.08}_{-0.07} \text{ (exp.) }^{+0.07}_{-0.06} \text{ (theo.)} .$$

It stays consistent with the results reported in this dissertation.

CHAPTER 5

Combination of Higgs properties measurements

5.1 Introduction

For the LHC Run 1, a combination of ATLAS and CMS measurements [94] was performed to determine the Higgs boson production and decay rates. More recently, with the Run 2 dataset recorded by the ATLAS detector during 2015, 2016 and 2017, using up to 79.8 fb^{-1} of proton–proton collision data produced by the LHC, the combined measurements of these measurements have been performed. This combination analysis takes inputs from analyses targeting the $H \rightarrow \gamma\gamma$ [93], $H \rightarrow ZZ^* \rightarrow 4\ell$ [93], $H \rightarrow WW^{(*)}$ [95] and $H \rightarrow \tau\tau$ [96] decay channels; analyses targeting $H \rightarrow b\bar{b}$ in associated production with a weak vector boson $V = W$ or Z (VH) [97, 98] and in the weak vector-boson fusion (VBF) production process [99]; two analyses targeting associated production with a top–antitop pair ($t\bar{t}H$) [93, 100, 101]; an analysis targeting the $H \rightarrow \mu\mu$ decay channel [102]; three analyses targeting Higgs decays to invisible final states [103, 104, 105]; and an analysis targeting off-shell production of Higgs bosons [11].

In these combined measurements, the Higgs boson mass used for SM prediction is $m_h = 125.09\text{ GeV}$, corresponding to the central value of the combination of the ATLAS and CMS measurements in Run 1 [39].

This chapter is structured as follows: Section 5.2 describes the data and simulation samples and Section 5.3 presents the analyses in individual decay channels which are used as inputs to the combination. The modifications applied to the statistical model of each input channel are described in Section 5.4. Section 5.5 provides a short description of the statistical procedures. Section 5.6 presents the measurement of the signal strength μ , defined as the ratio of the total Higgs boson signal yield to its SM prediction, as well as the production cross sections and the decay branching ratios measurement. Section 5.7 presents results in the STXS framework. Section 5.8 presents the potential deviations from SM predictions are then probed in a framework of multiplicative modifiers κ applied to the SM values

of Higgs boson couplings [2]. Finally, Section 5.9 summarizes the results.

5.2 Data and simulated samples

The 13 TeV proton–proton collision data collected by the ATLAS experiment [17, 21] in 2015, 2016 and 2017 are used. Different integrated luminosities of the datasets are used in each analysis are shown in Table 5.1. The analyses are described in Section 5.3.

Analysis	Integrated luminosity (fb ⁻¹)
$H \rightarrow \gamma\gamma$ (including $q\bar{q}/gg \rightarrow t\bar{t}H$, $H \rightarrow \gamma\gamma$)	79.8
$H \rightarrow ZZ^* \rightarrow 4\ell$ (including $q\bar{q}/gg \rightarrow t\bar{t}H$, $H \rightarrow ZZ^* \rightarrow 4\ell$)	79.8
$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$	36.1
$H \rightarrow \tau\tau$	36.1
VH , $H \rightarrow b\bar{b}$	79.8
VBF , $H \rightarrow b\bar{b}$	24.5 – 30.6
$H \rightarrow \mu\mu$	79.8
$t\bar{t}H$, $H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \rightarrow \text{invisible}$	36.1
Off-shell $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 2\ell 2\nu$	36.1

Table. 5.1: Integrated luminosity of the dataset used for each input analysis to the combination.

The simulated samples used to model the signal processes are described below. Simulated background samples are described in the individual references for the input analyses. As for the signal, a consistent set of simulated Higgs boson samples is used to describe the signal processes in most of the analysis. Only the VBF, $H \rightarrow b\bar{b}$, off-shell production analyses and measurements targeting decays of the Higgs boson to invisible final states use a dedicated set of signal samples, which are discussed at the end of this section.

Higgs boson production via gluon fusion is simulated using the Powheg-Box [53, 54, 55, 106] NNLOPS implementation [45, 107]. The event generator uses HNNLO [108] to reweight the inclusive Higgs boson rapidity distribution produced by the next-to-leading order (NLO) generation of $pp \rightarrow H + \text{parton}$, with the scale of each parton emission determined using the Minlo procedure [109]. The PDF4LHC15 [89] parton distribution functions (PDFs) are used for the central prediction and uncertainty. The sample is normalized such that it reproduces the total cross section predicted by a next-to-next-to-next-to-leading-order (N³LO) QCD calculation with NLO electroweak corrections applied [3, 50, 51, 49, 52]. The NNLOPS generator reproduces the Higgs boson p_T distribution predicted by the next-to-next-to-leading-order (NNLO) plus next-to-next-to-leading logarithm

(NNLL) calculation of HRES [110], which includes the effects of top- and bottom-quark masses and uses dynamical renormalization and factorization scales.

The VBF production process is simulated to NLO accuracy in QCD using the Powheg-Box [56] generator with the PDF4LHC15 set of PDFs. The sample is normalized to an approximate-NNLO QCD cross section with NLO electroweak corrections applied [3, 57, 58, 60].

The $qq \rightarrow VH$ production processes are simulated to NLO accuracy in QCD using the Powheg-Box, GoSam [111] and Minlo [112, 113] generators with the PDF4LHC15 set of PDFs. The samples are normalized to cross sections calculated at NNLO in QCD with NLO electroweak corrections [63, 66]. The $gg \rightarrow ZH$ process is generated only at leading order (LO), using Powheg-Box and NLO PDFs and normalized to an NLO computation with next-to-leading-logarithm (NLL) corrections [65, 3].

Higgs boson production in association with a top-antitop pair is simulated at NLO accuracy in QCD using the Powheg-Box generator with the PDF4LHC15 set of PDFs for the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay processes. For other Higgs boson decays, the MG5_aMC@NLO [67] generator is used with the NNPDF2.3 [68] set of PDFs. In both cases the sample is normalized to a calculation with NLO QCD and electroweak corrections [3, 69, 70, 71, 114].

In addition to the primary Higgs boson processes, separate samples are used to model lower-rate processes. Higgs boson production in association with a $b\bar{b}$ pair ($b\bar{b}H$) is simulated using MG5_aMC@NLO [73] with NNPDF2.3LO PDFs and is normalized to a cross section calculated to NNLO in QCD [3, 115, 116, 117]. The sample includes the effect of interference with the $gg \rightarrow H$ production mechanism. Higgs boson production in association with a single top quark and a W boson (tHW) is produced at LO accuracy using MG5_aMC@NLO with the CTEQ6L1 PDF set [118]. Finally, Higgs boson production in association with a single top quark in the t-channel (tHq) is generated at LO accuracy using MG5_aMC@NLO with CT10 [74] PDFs. The tH samples are normalized to NLO QCD calculations [3, 119].

The parton-level events are input to Pythia8 [46] or Herwig++ [75] to model the Higgs boson decay, parton showering, hadronization, and multiple parton interaction (MPI) effects. The generators are interfaced to Pythia8 for all samples except tHW . For Pythia8 the AZNLO and A14 parameter sets [47] are used, and for Herwig++ its UEEE5 [120] parameter set is used.

In the all-hadronic channel of the VBF, $H \rightarrow b\bar{b}$ analysis, the Powheg-Box generator with the CT10 [74] set of PDFs is used to simulate the ggF [121] and VBF production processes, and interfaced with Pythia8 for parton shower. In the photon channel of the VBF, $H \rightarrow b\bar{b}$ analysis, VBF and ggF production

in association with a photon is simulated using the MG5_aMC@NLO generator with the PDF4LHC15 set of PDFs, and also using Pythia8 for parton shower. For both channels, contributions from $q\bar{q} \rightarrow WH/ZH$ and $q\bar{q}/gg \rightarrow t\bar{t}H$ production are generated using the Pythia8 generator with the NNPDF2.3 set of PDFs, and using the MG5_aMC@NLO generator interfaced with Herwig++ and the NLO CT10 set of PDFs, respectively.

In the analyses targeting Higgs boson decays to invisible final states, the ggF, VBF and ZH signals are simulated in a similar way to the general procedure described above, but for the VBF production process the NNPDF2.3 PDF set is used instead of PDF4LHC15, while for the ZH process the CT10 PDF set is used.

In the off-shell production analysis, the $gg \rightarrow H^* \rightarrow ZZ$ process is generated together with the corresponding irreducible continuum production, using the Sherpa 2.2.2 + OpenLoops [122, 78, 123, 124] generator and the NNPDF2.3 PDF set. The generation is performed at leading order with up to one additional jet in the final state, and interfaced with the Sherpa parton shower [125]. The cross section calculations take into account K -factors following the methodology described in Ref. [11].

The particle-level Higgs boson events are passed through a Geant4 [25, 26] simulation of the ATLAS detector [23] and reconstructed using the same analysis software as used for the data. Event pileup is included in the simulation by overlaying inelastic proton–proton collisions, such that the average number of interactions per bunch crossing reproduces that observed in the data. The inelastic proton–proton collisions are simulated with Pythia8 using the MSTW2008lo [126] set of PDFs with the A2 [127] set of tuned parameters.

5.3 Individual channel measurements

In the combination effort, the statistic model with signal divided in STXS regions are used for all channels other than VBF, $H \rightarrow b\bar{b}$, $H \rightarrow \mu\mu$, H decay to invisible and off-shell production analysis. STXS regions are then merged to provide all kinds of measurements. Brief descriptions of the input analyses to the combination are given below. More details can be found in the individual analysis references listed in each section. The categorization is summarized in Table 5.2. The overlap between the event selections of the analyses included in the combination is found to be negligible.

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow \tau\tau$	$H \rightarrow b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 $\ell + 2 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 opposite-sign $\ell + 1 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H \rightarrow ZZ^* \rightarrow 4\ell$) $t\bar{t}H$ leptonic, $H \rightarrow ZZ^* \rightarrow 4\ell$ $t\bar{t}H$ hadronic, $H \rightarrow ZZ^* \rightarrow 4\ell$			$t\bar{t}H$ 1 ℓ , boosted $t\bar{t}H$ 1 ℓ , resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ , $p_{\text{T}}^{\ell+\text{MET}} \geq 150$ GeV VH 1 ℓ , $p_{\text{T}}^{\ell+\text{MET}} < 150$ GeV VH $E_{\text{T}}^{\text{miss}}, E_{\text{T}}^{\text{miss}} \geq 150$ GeV VH $E_{\text{T}}^{\text{miss}}, E_{\text{T}}^{\text{miss}} < 150$ GeV $VH+VBF$ $p_{\text{T}}^{j1} \geq 200$ GeV VH hadronic (2 categories)	VH leptonic 0-jet, $p_{\text{T}}^{4\ell} \geq 100$ GeV 2-jet, $m_{jj} < 120$ GeV			2 ℓ , $75 \leq p_{\text{T}}^V < 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ , $75 \leq p_{\text{T}}^V < 150$ GeV, $N_{\text{jets}} \geq 3$ 2 ℓ , $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 2 ℓ , $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} \geq 3$ 1 ℓ $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 1 ℓ $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} = 3$ 0 ℓ , $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} = 2$ 0 ℓ , $p_{\text{T}}^V \geq 150$ GeV, $N_{\text{jets}} = 3$
VBF	VBF , $p_{\text{T}}^{\gamma jj} \geq 25$ GeV (2 categories) VBF , $p_{\text{T}}^{\gamma jj} < 25$ GeV (2 categories)	2-jet VBF , $p_{\text{T}}^{j1} \geq 200$ GeV 2-jet VBF , $p_{\text{T}}^{j1} < 200$ GeV	2-jet VBF	VBF $p_{\text{T}}^{\tau\tau} > 140$ GeV ($\tau_{\text{had}}\tau_{\text{had}}$ only) VBF high- m_{jj} VBF low- m_{jj}	VBF , two central jets VBF , four central jets $VBF+\gamma$
$gg \rightarrow H$	2-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 2-jet, $120 \text{ GeV} \leq p_{\text{T}}^{\gamma\gamma} < 200$ GeV 2-jet, $60 \text{ GeV} \leq p_{\text{T}}^{\gamma\gamma} < 120$ GeV 2-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} \geq 200$ GeV 1-jet, $120 \text{ GeV} \leq p_{\text{T}}^{\gamma\gamma} < 200$ GeV 1-jet, $60 \text{ GeV} \leq p_{\text{T}}^{\gamma\gamma} < 120$ GeV 1-jet, $p_{\text{T}}^{\gamma\gamma} < 60$ GeV 0-jet (2 categories)	1-jet, $p_{\text{T}}^{4\ell} \geq 120$ GeV 1-jet, $60 \text{ GeV} \leq p_{\text{T}}^{4\ell} < 120$ GeV 1-jet, $p_{\text{T}}^{4\ell} < 60$ GeV 0-jet, $p_{\text{T}}^{4\ell} < 100$ GeV	1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 1-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} < 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} < 20$ GeV 0-jet, $m_{\ell\ell} \geq 30$ GeV, $p_{\text{T}}^{\ell_2} \geq 20$ GeV	Boosted, $p_{\text{T}}^{\tau\tau} > 140$ GeV Boosted, $p_{\text{T}}^{\tau\tau} \leq 140$ GeV	

Table. 5.2: Summary of the signal regions entering the combined measurements. Each 0-jet and 1-jet $H \rightarrow WW^{(*)}$ entry corresponds to two categories for a leading lepton flavor of either e or μ . For $H \rightarrow \tau\tau$, each entry corresponds to 3 categories for $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ unless otherwise specified. “Multilepton” refers to decays of the Higgs boson with one or more leptons, and encompasses $H \rightarrow WW^{(*)}$, $H \rightarrow \tau\tau$, and $H \rightarrow ZZ^{(*)}$ excluding $H \rightarrow ZZ^* \rightarrow 4\ell$. The selections targeting $H \rightarrow \mu\mu$, $H \rightarrow$ invisible and off-shell Higgs boson production are not included this table.

5.3.1 $H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ analysis [128] (Chapter 4) are then updated with the 79.8 fb^{-1} of proton–proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and recorded by the ATLAS detector in 2015–2017 [93] and then taken into combination. The most significant change is that seven categories are updated to select $t\bar{t}H$ production, including both leptonic and hadronic top decay processes. The other categorization selections targeting the ggF VBF and VH production modes and the analysis strategy stay the same. This analysis requires the presence of two isolated photons [29] within the pseudorapidity range $|\eta| < 2.37$, excluding the region $1.37 < |\eta| < 1.52$ corresponding to the transition between the barrel and endcap sections of the electromagnetic calorimeter. The transverse momenta of the leading and subleading photons are required to be greater than $0.35m_{\gamma\gamma}$ and $0.25m_{\gamma\gamma}$ respectively, where $m_{\gamma\gamma}$ is the invariant mass of the diphoton system. The distribution of $m_{\gamma\gamma}$ is used to separate the Higgs boson signal from continuum background processes.

Events selected are separated into 29 exclusive categories based on the kinematics of the diphoton system and associated particles, chosen to approximately match those of the Stage 1 STXS regions described in Section 5.7.1.

As mentioned above, seven categories are defined to select $t\bar{t}H$ production, including both leptonic and hadronic top decay processes through various selections on the multiplicities and kinematics of leptons [32, 129], jets [130], and jets tagged as containing b -hadrons [131].

The remaining events are classified into categories targeting the VH , VBF and ggF production modes. A detailed description of those categories can be found in Section 4.4.

5.3.2 $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

The $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis reconstructs the intermediate Z bosons using their decays to electrons and muons by requiring the presence of at least two same-flavor and opposite-charge light-lepton pairs. The four-lepton invariant mass is required to be between 118 and 129 GeV.

The analysis follows the strategy described in the previous publication [132], but employs improved event reconstruction and electron reconstruction [133] techniques, and defines additional event categories to enhance sensitivity to the production of the SM Higgs boson associated with a vector boson (VH , $V \rightarrow \ell\nu/\nu\nu$) and with a top quark pair [93]. 11 mutually exclusive reconstructed event categories are used to separate the different Higgs boson production modes and the kinematic regions of the STXS framework, including 2 $t\bar{t}H$ -enriched categories,

3 VH categories, 2 categories targeting the VBF production mode and 4 ggF categories. In the categories where a BDT is employed, the signal is extracted through a binned fit to the BDT discriminant, while the signal estimation in other categories is based on event counting.

The largest continuum $(Z^{(*)}/\gamma^*)(Z^{(*)}/\gamma^*)$ background is modeled with Sherpa for production via quark (gluon) annihilation, and normalized to an NNLO QCD plus NLO electroweak (NLO QCD) calculation. Other background contributions arise from $Z + \text{jets}$ and $t\bar{t}$ production with two prompt leptons and are estimated using control regions in the data.

5.3.3 $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$

The $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ analysis [95] targets the ggF and VBF production modes, with W boson decaying to $e^\pm\nu$, $\mu^\mp\nu$ and also $W \rightarrow \tau\nu$ decays in which the tau leptons subsequently decay into electrons or muons.

16 mutually exclusive reconstructed event categories are used to classify events to target the ggF production mode, based on the jet multiplicity, the flavor of the leading lepton, the invariant mass of the dilepton system $m_{\ell\ell}$ and the transverse momentum of the sub-leading lepton $p_{\text{T}}^{\ell_2}$. according to the number of associated jets (N_{jets}). There is also a $N_{\text{jets}} \geq 2$ categories naturally sensitive to the VBF process developed. Events with jets tagged as containing b -hadrons are rejected to suppress background contributions originating from top-quark production.

The primary background processes are WW , top-quark, $W + \text{jets}$, Drell–Yan, and other diboson (WZ , $W\gamma$, $W\gamma^*$, and ZZ) production. Most of these contributions are estimated using data in kinematic regions enriched in the given process.

5.3.4 $H \rightarrow \tau\tau$

The $H \rightarrow \tau\tau$ analysis [96] measures the Higgs boson production cross section in the VBF production process or in “boosted” ggF production with large Higgs boson transverse momentum p_{T}^H . 3 VBF categories and 2 “boosted” high- p_{T}^H ggF categories are developed. For most the categories, three mutually exclusive analysis channels are included in each category, including $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, and $\tau_{\text{had}}\tau_{\text{had}}$, are defined according to the number of selected electron, muon and hadronic tau candidates. The exception is one VBF category is defined by requiring the transverse momentum of the $\tau\tau$ system $p_{\text{T}}^{\tau\tau}$ to be above 140 GeV, for $\tau_{\text{had}}\tau_{\text{had}}$ events only.

The distribution of the invariant mass of the di-tau system is used to separate the Higgs boson signal from background. In all three sub-channels, the most important backgrounds are irreducible $Z \rightarrow \tau\tau$ events, and events with one or

two jets misidentified as tau lepton decay products, primarily from multijet and W +jets production.

5.3.5 $H \rightarrow b\bar{b}$

The $H \rightarrow b\bar{b}$ decay channel covers the production cross section in the VH and VBF production modes.

The $VH, H \rightarrow b\bar{b}$ analysis [97, 98] considers final states containing at least two jets that must be tagged as containing b -hadrons. Either zero, one or two charged leptons are also required, exploring the associated production of a Higgs boson with a W or Z boson decaying leptonically.

According to the the vector boson transverse momentum p_T^V , the charged lepton multiplicity, and the jet multiplicity, 8 reconstructed categories are developed to enhance the signal sensitivity.

The largest background contributions arise from V +heavy-flavor-jets and $t\bar{t}$ production which is estimated using data. The normalizations of single-top-quark and diboson (WZ and ZZ) production are obtained from theory predictions, while their shapes are taken from simulation. There are small multijet contamination due to jets mis-measured in the calorimeters and are estimated using data-driven control samples.

In the VBF, $H \rightarrow b\bar{b}$ analysis [99], three orthogonal selections are employed, targeting two all-hadronic channels and a photon-associated channel. Each selection requires the presence of at least two jets tagged as containing b -hadrons in the central pseudorapidity region $|\eta| < 2.5$ as well as at least two additional jets used to identify the $qq' \rightarrow qq'H$ topology. The two orthogonal all-hadronic selections are categorized by the multiplicity of central/forward jets and jet triggers are used, while the VBF+ γ selection is using the photon trigger.

The non-resonant production of b -tagged jet pairs is the dominant background. There are also smaller contributions from $Z \rightarrow b\bar{b}$ production. The non-resonant background yields in the photon-associated channel are about two orders of magnitude lower than in the other two VBF selections. The VBF, $H \rightarrow b\bar{b}$ channels are included in all the measurements except for those presented in Section 5.7.

5.3.6 $H \rightarrow \mu\mu$

The analysis strategy of $H \rightarrow \mu\mu$ search [102] is similar to the $H \rightarrow \gamma\gamma$ analysis. A pair of opposite-charge muons is selected and then the distribution of the invariant mass $m_{\mu\mu}$ is used in fitting to separate signal from background. Events are classified into eight categories, including two VBF-enriched categories classi-

fied with BDT exploiting the kinematic properties of the two leading jets and the two muons, and six ggF-categories classified into three ranges of the transverse momentum $p_T^{\mu\mu}$ of the dimuon system and the muon pseudorapidities η^μ . The dominant background process is the Drell-Yan background. This channel is only included in the results presented in Section 5.8.3.

5.3.7 $t\bar{t}H$, $H \rightarrow b\bar{b}$ and $t\bar{t}H$ multilepton analyses

The $t\bar{t}H$ analysis contains 4 channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow b\bar{b}$ [101] and multilepton final states, targeting Higgs boson decays to WW^* , ZZ^* and $\tau\tau$ [93, 100]. The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ $t\bar{t}H$ analyses are already included in the coupling analyses mentioned in Sections 5.3.1 and 5.3.2 .

The search for $t\bar{t}H$ production with $H \rightarrow b\bar{b}$ employs two selections, optimized for single-lepton and dilepton final states of $t\bar{t}$ decays. In the single lepton channel, events are required to have one isolated electron or muon and at least five jets, of which at least two must be identified as containing b -hadrons, candidate events are then classified into eleven orthogonal categories, according to the values of the b -tagging discriminant for the jets and the jet multiplicity. A special “boosted” category is also included in the single lepton channel. In the dilepton channel, events are required to have two opposite-charge leptons and at least three jets, of which at least two must be identified as containing b -hadrons. Seven orthogonal categories are developed.

In each of the category, a BDT selection is employed to separate $t\bar{t}H$ production from background processes. Some of the selected regions are enriched in the main background processes, $t\bar{t} + \text{light flavor}$, $t\bar{t} + \geq 1b$, $t\bar{t} + \geq 1c$, $t\bar{t} + V$ and non- $t\bar{t}$.

The $t\bar{t}H$ multilepton analysis with Higgs boson decays to WW^* , ZZ^* and $\tau\tau$ exploits seven final states, categorized by the number and flavor of reconstructed charged lepton candidates, are examined. The number, the charge and the flavor of leptons, the number of hadronic τ candidates are used in splitting candidate events to different categories.

The leptons produced in heavy-flavor decays, from electron charge misreconstruction in events where opposite-sign leptons are produced and from the production of $t\bar{t} + W/Z$, photon conversions or misidentified hadronic jets are the major source of background. Multivariate discriminant techniques are used in most channels to improve the sensitivity.

5.3.8 Searches for invisible Higgs boson decays

Searches for decays of the Higgs boson to invisible final states are performed in three analysis in which events with large missing transverse momentum are selected. In the VBF analysis, major backgrounds are suppressed by requiring addition jets in a VBF topology [103]. While in ZH analysis [104] charged leptons decayed from Z boson are required. And the associated W or Z boson decaying to hadronic final states are used in the VH -hadronic analysis [105].

In the VBF analysis, the missing transverse momentum is required to be larger than 180 GeV. The leading background processes, $(Z \rightarrow \ell^+ \ell^-) + \text{jets}$ production and $(W \rightarrow \ell \nu) + \text{jets}$ production with an undetected charged lepton, are estimated in control region data and extrapolated to the signal region using MC simulations.

In the analysis with a leptonically decaying Z boson, The missing transverse momentum is required to be larger than 90 GeV. The dominant background processes are the non-resonant diboson productions which are estimated from simulation, including $(Z \rightarrow \ell^+ \ell^-)(Z \rightarrow \nu \nu)$ and $(Z \rightarrow \ell^+ \ell^-)(W \rightarrow \ell \nu)$ production with an additional undetected charged lepton.

Both the resolved and the boosted event topologies are considered to identify production in association with a hadronically decaying W and Z boson. The missing transverse momentum is required to be larger than 150 GeV and 250 GeV for the resolved and boosted topologies respectively. Events are categorized according to the multiplicity of jets tagged as containing b -quarks in both of the cases. There is a separate category defined for events in which the mass of the jet system, defined as the dijet mass in the resolved topology and the mass of the large-radius jet in the merged topology. The main backgrounds, from $W + \text{jets}$, $Z + \text{jets}$ and $t\bar{t}$ production, are estimated from control regions in data.

The statistical combination of these analyses gives an observed (expected) upper limit on the branching ratio for Higgs boson decays to invisible final states of $B_{\text{inv}} < 0.38$ (0.21) at 95% confidence level. These analyses are only included in the coupling measurements presented in Sections 5.8.2 and 5.8.4.

5.3.9 Off-shell Higgs boson production

The off-shell coupling strength of the observed Higgs boson is measured through the $H^* \rightarrow ZZ$ final state in the mass range above the $2m_Z$ threshold (off-shell region). There are two analysis, $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ [11] contained in these measurements.

Assuming that the on-shell and off-shell coupling modifiers are the same, and that the ratio of the Higgs boson couplings to the SM predictions is independent of the momentum transfer of the Higgs production mechanism considered in the

analysis, the total width of the Higgs boson can be constrained from a combination with the on-shell measurements. It is also assumed that any new physics which modifies the off-shell signal strength and the off-shell couplings does not modify the relative phase of the interfering signal and background processes. Further, it is assumed that there are neither sizeable kinematic modifications to the off-shell signal nor new sizeable signals in the search region of this analysis unrelated to an enhanced off-shell signal strength [134, 135].

The analysis in the $ZZ \rightarrow 4\ell$ final state follows closely the Higgs boson measurements in the same final state, described in Section 5.3.2. The off-peak region is defined to cover the range $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$. As for the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis, the background is dominated by $q\bar{q}/gg \rightarrow ZZ$ production.

The analysis in the $ZZ \rightarrow 2\ell 2\nu$ channel is similar to the one designed to search for heavy ZZ resonances [136] with the same object definitions. The transverse mass (m_{T}^{ZZ}) [11], reconstructed from the momentum of the dilepton system and the missing transverse momentum, is chosen as the discriminating variable. Events in the range $250 \text{ GeV} < m_{\text{T}}^{ZZ} < 2000 \text{ GeV}$ are used in a binned maximum likelihood fit for the final result. SM ZZ and WZ production are the major backgrounds.

These off-shell analyses are only included in the coupling measurements presented in Section 5.8.4.

5.4 Combination procedure

5.4.1 Input likelihood model modification

The modifications implemented to the input analysis are summarized in this section.

The combination takes two types of likelihood models from each channel: one with full theory uncertainty on signal and used for the global signal strength and κ results, denoted as μ model, and the other with only theory uncertainty on acceptance of signal, denoted as cross-section model. For all channels except for $H \rightarrow \mu\mu$ and VBF, $H \rightarrow b\bar{b}$ (which have limited sensitivity and thus only split into inclusive production modes), the Higgs signal is split into full granularity of Stage 1 STXS framework (Section 1.3).

For the cross-section model, only the acceptance uncertainty on each STXS bin is applied. When the bins are merged to provide measurements in coarser granularity, additional theory uncertainties need to be injected due to the assumption of SM predicted fraction between bins. For the μ model, merging signal strength parameters is straightforward as full theory uncertainties have been considered. The merging of STXS bins will be discussed in Section 5.4.2.

In addition, to facilitate proper correlation of luminosity and branching ratio uncertainties between channels, these two uncertainties are re-parameterized following the description in Section 5.4.3 and 5.4.4.

5.4.2 Procedure for merging STXS bins

To perform combined STXS-style measurements, all the relevant input channels have implemented Stage 1 STXS framework. The implementation not only includes splitting of the signal into STXS truth bins, but also includes proper treatment of QCD scale and PDF+ α_S uncertainties.

5.4.2.1 Central values

The number of signal events in reconstruction category r , n_r , can be expressed as the sum of contribution from each STXS truth bin t

$$n_r = \sum_t \epsilon_{tr}^{SM} \mathcal{L}(B\sigma_t)^{SM} \mu_t \quad (5.1)$$

Here ϵ_{tr}^{SM} is the efficiency of STXS truth bin t in reconstruction category r as predicted by SM, which could be calculated with number of signal events entering truth bin t , n_t^{SM} , and number signal events entering both truth bin t and reco category r , n_{tr}^{SM}

$$\epsilon_{tr}^{SM} = \frac{n_{tr}^{SM}}{n_t^{SM}} \quad (5.2)$$

$\mathcal{L}$ is the luminosity, $(B\sigma_t)^{SM}$ is the SM predicted branching ratio times cross section in bin t . μ_t is the scale factor on the SM prediction and will be fitted as the parameter of interest (POI). In the μ model, μ_t is the signal strength. In the cross section model, μ_t represents the fitted cross-section value in the unit of corresponding SM prediction. The reasons for introducing μ_t as parameter of interest, in particular for model without normalization theoretical systematics, are the following

- Convenient for merging truth bins. Truth bin merging is frequently exercised in our measurements, e.g. reducing STXS Stage 1 granularity, measuring the cross-section of each production mode, etc.
- Convenient for understanding the fitting results: unity means agreement with SM prediction.

For channels with generator-level filter, the number of events in truth bin t directly derived from the sample is biased by the filter efficiency, ϵ_{filter} , and needs to be corrected for when calculating ϵ_{tr}^{SM} using the following formula

$$n_t^{SM} = \frac{n_{tot}^\epsilon}{\epsilon_{filter}} A_t = \frac{n_t^\epsilon}{A_t^\epsilon \epsilon_{filter}} A_t \quad (5.3)$$

Here n_{tot}^ϵ is the total number of events from the sample with filter, n_t^ϵ is the number of events in truth bin t as derived from the sample with filter, and A_t^ϵ is the acceptance of truth bin t as derived from the sample with filter. A_t is the central acceptance value of truth bin t without any filter. In addition, the value of SM prediction $(B\sigma_t)^{SM}$ should also be calculated using these values

5.4.2.2 Uncertainties

To simplify the description without losing generality, all the uncertainties discussed below are assumed to be Gaussian-constrained (in reality, the constraint pdf can also be log-normal or other types), with the uncertainty magnitude denoted as δ and the nuisance parameter denoted as θ . Uncertainties from a certain source could also affect the shape of the template. In such a case, variations in the shape should be properly correlated with the corresponding variations in the yield.

For uncertainties on luminosity, it is straightforward to implement in Eq. 5.1 as:

$$\sum_t \epsilon_{tr}^{SM} \mathcal{L}(1 + \theta^L \delta^L) (B\sigma_t)^{SM} \mu_t \quad (5.4)$$

Other experimental uncertainties would affect ϵ_{tr}^{SM} by manifesting as variations δ_{tr}^{exp} on the numerator n_{tr}^{SM} . Therefore the uncertainties can be implemented as

$$\sum_t \epsilon_{tr}^{SM} (1 + \theta^{exp} \delta_{tr}^{exp}) \mathcal{L}(B\sigma_t)^{SM} \mu_t \quad (5.5)$$

Theory uncertainties will affect both n_{tr}^{SM} and n_t^{SM} . Assume the variations on each component are δ_{tr} and δ_t , respectively, then the theory uncertainty on ϵ_{tr}^{SM} , δ_{tr}^ϵ , can be implemented as:

$$\begin{aligned} \sum_t \epsilon_{tr}^{SM} (1 + \theta \delta_{tr}^\epsilon) \mathcal{L}(B\sigma_t)^{SM} \mu_t &= \sum_t \epsilon_{tr}^{SM} \frac{1 + \theta \delta_{tr}}{1 + \theta \delta_t} \mathcal{L}(B\sigma_t)^{SM} \mu_t \\ &\sim \sum_t \epsilon_{tr}^{SM} [1 + \theta(\delta_{tr} - \delta_t)] \mathcal{L}(B\sigma_t)^{SM} \mu_t \end{aligned} \quad (5.6)$$

Equation. 5.6 is corresponding to the implementation of signal yield in the cross-section model. Here in the last step, the uncertainty on the denominator has been Talyor-expanded to the first order. The approximation is introduced to

ease the implementation.

In the μ model, we need to assign additional uncertainty on the SM prediction $(B\sigma_t)^{SM}$:

$$\begin{aligned} \sum_t \epsilon_{tr}^{SM} (1 + \theta \delta_{tr}^\epsilon) \mathcal{L}(B\sigma_t)^{SM} (1 + \theta \delta_t) \mu_t &= \sum_t \epsilon_{tr}^{SM} \frac{1 + \theta \delta_{tr}}{1 + \theta \delta_t} \mathcal{L}(B\sigma_t)^{SM} (1 + \theta \delta_t) \mu_t \\ &= \sum_t \epsilon_{tr}^{SM} (1 + \theta \delta_{tr}) \mathcal{L}(B\sigma_t)^{SM} \mu_t \end{aligned} \quad (5.7)$$

So in the μ model, effectively we are only considering the variation on the numerator n_{tr}^{SM} in ϵ_{tr}^{SM} .

For channels with filters, evaluation of δ_t may also be biased by the filter efficiency.

5.4.2.3 Merging truth bins

The implemented Stage 1 STXS truth binning usually cannot be directly used for fitting because the granularity is too fine given current data statistics. Instead, we usually need to reduce the granularity to a reasonable level by merging some truth bins together. Also, we often would like to measure a specific group of truth bins.

For the μ model, since the full theory uncertainties have been considered, merging truth bins is as trivial as equating the relevant POIs μ_t .

For the cross-section model, when merging truth bins we are imposing additional assumptions on the relative fraction of each merged bin following SM prediction. Hence besides equating μ_t , we also need to inject the additional theory uncertainties introduced by the merging.

Consider the simplest case where we merge two truth bins with indices “1” and “2” into one truth bin “12”. In reconstruction category r , originally in the two bins we have

$$\epsilon_{1,2r}^{SM} \mathcal{L}(B\sigma_{1,2})^{SM} \mu_{1,2} \quad (5.8)$$

After merging, we have $\mu_1 = \mu_2 = \mu_{12}$. Denote $\sigma_{12} = \sigma_1 + \sigma_2$, in bin “1” we should now have

$$\epsilon_{1r}^{SM} \mathcal{L}(B\sigma_1)^{SM} \mu_{12} = \frac{n_{1r}^{SM}}{n_1^{SM}} \mathcal{L}(B\sigma_{12})^{SM} \frac{n_1^{SM}}{n_1^{SM} + n_2^{SM}} \mu_{12} = \frac{n_{1r}^{SM}}{n_1^{SM} + n_2^{SM}} \mathcal{L}(B\sigma_{12})^{SM} \mu_{12} \quad (5.9)$$

Here we rewrite σ_1 in terms of σ_{12} to reflect the additional model assumption

imposed by merging the two truth bins. So the theory uncertainty for the merged bin “12” should reflect the variations on n_{1r}^{SM} , n_1^{SM} and n_2^{SM} . With some simple algebra we could get the new uncertainty to be multiplied to the efficiency factor ϵ_{1r}^{SM}

$$1 + \theta(\delta_{1r} - \frac{n_1^{SM}\delta_1 + n_2^{SM}\delta_2}{n_1^{SM} + n_2^{SM}}) \quad (5.10)$$

Compared with the original uncertainty on truth bin “1” in reconstruction category r , $\delta_{1r} - \delta_1$, the extra uncertainty added is

$$\Delta\delta_1 = \delta_1 - \frac{n_1^{SM}\delta_1 + n_2^{SM}\delta_2}{n_1^{SM} + n_2^{SM}} \quad (5.11)$$

This can be easily generalized to the situation of merging an arbitrary number of truth bins. Let index i run over all the truth bins to be merged, then the additional theory uncertainty to be applied to truth bin t can be expressed as

$$\Delta\delta_t = \delta_t - \frac{\sum_i n_i^{SM}\delta_i}{\sum_i n_i^{SM}} \quad (5.12)$$

The additional uncertainty does not depend on the reconstruction level selection since the assumption made is only between truth bins.

The Tables 5.3 and 5.4 show the additional PDF and QCD scale uncertainties when merging STXS stage 1 bins into five production modes (ggF, VBF, WH , ZH , $t\bar{t}H$). Uncertainties with a contribution smaller than 0.5% are ignored. The uncertainties in the Tables 5.3 and 5.4 are injected into $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$ and $H \rightarrow \tau\tau$ input channels.

The STXS granularities in the $VH \rightarrow b\bar{b}$ channel are different with other channels (3 for the WH , 3 for the $qqZH$ and 3 for the $ggZH$), also the uncertainty schema are different. The dedicated PDF and QCD scale additional uncertainties when merging the stage 1 bins into WH and ZH production modes are summarized in the Tables 5.5 and 5.6. The uncertainty less than 0.5% will be ignored. The uncertainties are only injected into the $VH \rightarrow b\bar{b}$ input channel.

5.4.2.4 Treatment of $b\bar{b}H$ and $ggZH$ production modes

In the STXS measurements, $b\bar{b}H$ should be merged into $gg \rightarrow H$. But in the $H \rightarrow \gamma\gamma$ channel, there is only 1 $b\bar{b}H$ bin, which cannot be merged into multiple gg2H Stage 1 bins. Thus in the STXS measurements, the cross sections of gg2H Stage 1 bins are scaled by $(\sigma_{ggF} + \sigma_{b\bar{b}H})/\sigma_{ggF}$. The scale is only applied to the channel where there are $b\bar{b}H$ categories ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$).

There are 9 VHlep Stage 1 bins in the $VH \rightarrow b\bar{b}$: 3 production modes ($q\bar{q} \rightarrow WH/ZH$, $ggZH$) times 3 p_T^V bins ($[0, 150]$, $[150, 250]$, $[250, \infty]$ GeV). While the

	EV1	EV2	EV3	EV4	EV5	EV6	EV7	EV8	EV9	EV10	EV11	EV12	EV13	EV14	EV15	EV16	EV17	EV18	EV19	EV20	EV21	EV22	EV23	EV24	EV25	EV26	EV27	EV28	EV29	EV30	alphaS	Tot
gg2H_0l	0.01	0.08	0.01	0.27	0.38	0.07	0.00	0.01	0.05	-0.01	0.08	-0.04	-0.02	0.02	0.05	0.05	-0.33	-0.01	0.08	-0.02	-0.01	-0.06	-0.02	0.04	>0.01	-0.02	<0.01	-0.07	<0.01	0.02	-0.84	1.04
gg2H_1l_pH_0_60	0.01	-0.02	0.01	-0.23	-0.22	-0.13	0.00	0.00	-0.05	-0.01	-0.02	0.06	-0.02	0.02	-0.05	-0.05	0.27	-0.01	-0.02	0.08	-0.01	0.04	-0.02	-0.06	>0.01	-0.02	<0.01	0.03	<0.01	0.02	1.16	1.25
gg2H_1l_pH_60_120	0.01	-0.12	0.01	-0.43	-0.62	-0.13	0.00	-0.01	-0.05	-0.01	-0.12	0.06	0.08	-0.08	-0.05	-0.05	0.57	-0.01	-0.12	-0.02	<0.01	0.04	0.08	-0.06	>0.01	0.08	<0.01	0.13	<0.01	-0.08	1.46	1.78
gg2H_1l_pH_120_200	-0.09	-0.22	-0.09	-0.73	-1.32	-0.23	0.00	-0.01	-0.15	0.09	-0.32	0.06	0.08	-0.08	-0.15	-0.25	1.87	0.09	-0.32	-0.02	<0.01	0.24	0.08	-0.06	0.10	0.08	<0.01	0.23	<0.01	-0.08	1.56	2.46
gg2H_1l_pH_200_300	-0.19	-0.52	-0.09	-1.13	-2.22	-0.43	0.00	-0.11	-0.25	-0.01	-0.52	-0.04	0.18	-0.08	-0.15	-0.25	1.17	0.09	-0.32	-0.02	-0.10	0.64	0.08	-0.06	>0.01	0.08	<0.01	0.33	<0.01	-0.08	1.56	3.44
gg2H_ge2l_pH_0_60	0.01	-0.02	0.01	-0.33	-0.32	-0.03	0.00	-0.01	-0.05	-0.01	-0.12	0.06	-0.02	-0.08	-0.05	-0.05	0.37	-0.01	-0.02	-0.02	<0.01	0.04	-0.02	-0.06	>0.01	0.08	<0.01	0.13	<0.01	-0.02	1.46	1.98
gg2H_ge2l_pH_60_120	0.01	-0.22	0.01	-0.63	-0.82	-0.13	0.00	-0.01	-0.15	0.09	-0.22	0.06	0.08	-0.08	-0.15	-0.15	0.67	0.09	-0.12	-0.02	<0.01	0.04	0.08	-0.06	>0.01	0.08	<0.01	0.23	<0.01	-0.08	1.56	2.56
gg2H_ge2l_pH_120_200	-0.09	-0.32	-0.09	-0.83	-1.32	-0.33	0.00	-0.01	-0.15	0.09	-0.32	0.06	0.08	-0.08	-0.15	-0.25	1.97	0.09	-0.32	-0.02	-0.10	0.24	0.08	-0.06	>0.01	0.08	<0.01	0.33	<0.01	-0.08	1.46	3.57
gg2H_ge2l_pH_200_300	-0.19	-0.62	-0.09	-1.13	-2.32	-0.63	0.00	-0.11	-0.35	-0.01	-0.52	-0.04	0.18	-0.08	-0.15	-0.25	1.27	0.19	-0.62	-0.02	-0.10	0.64	0.08	-0.06	0.10	0.18	<0.01	0.33	<0.01	-0.08	1.56	2.17
gg2H_VBFtopo_jet3veto	-0.09	-0.42	-0.09	-0.43	-1.22	-0.13	0.00	-0.01	-0.15	-0.01	-0.22	0.06	0.08	-0.08	-0.15	-0.15	0.77	-0.01	-0.12	0.08	<0.01	0.24	0.08	-0.06	0.10	0.08	<0.01	0.03	<0.01	-0.08	1.56	2.42
gg2H_VBFtopo_jet3	-0.09	-0.32	-0.09	-0.63	-1.32	-0.23	0.00	-0.01	-0.15	-0.01	-0.32	0.06	0.08	-0.08	-0.15	-0.15	0.77	0.09	-0.32	0.18	-0.10	0.34	0.08	-0.06	0.10	0.08	<0.01	0.13	<0.01	-0.08	1.56	2.42
VBF_qq2Hqq_VBFtopo_jet3veto	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
VBF_qq2Hqq_VBFtopo_jet3	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
VBF_qq2Hqq_VH2jet	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
VBF_qq2Hqq_rest	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
VBF_qq2Hqq_pTjet1_gt200	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
WH_qq2Hqq_VBFtopo_jet3	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
WH_qq2Hqq_VH2jet	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
WH_qq2Hqq_rest	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
WH_qq2Hqq_pTjet1_gt200	-0.10	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hlum_pTV_0_150	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hlum_pTV_150_250_0j	-0.10	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hlum_pTV_150_250_ge1j	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hlum_pTV_ge250	<0.01	>-0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
ZH_qq2Hqq_VBFtopo_jet3veto	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
ZH_qq2Hqq_VBFtopo_jet3	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
ZH_qq2Hqq_VH2jet	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
ZH_qq2Hqq_rest	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
ZH_qq2Hqq_pTjet1_gt200	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hll_pTV_0_150	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hll_pTV_150_250_0j	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hll_pTV_150_250_ge1j	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01
qq2Hll_pTV_ge250	<0.01	<0.01	0.00	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01	<0.01	<0.01	<0.01	>-0.01	<0.01	>-0.01	<0.01	<0.01	<0.01	>-0.01	>-0.01	0.00	>-0.01	<0.01	>-0.01	>-0.01	0.00	<0.01	>-0.01	<0.01	<0.01

Table. 5.3: Additional PDF uncertainties when merging STXS stage 1 bins into five production modes (ggF, VBF, WH , ZH , $t\bar{t}H$). The uncertainties are injected into $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$ and $H \rightarrow \tau\tau$ input channels. The last “Tot” column is from quadratic sum of independent sources.

STXS bin [%]	ggF_mu	ggF_res	ggF_qm_t	ggF_mig01	ggF_mig12	ggF_vbf2j	ggF_vbf3j	ggF_pTH60	ggF_pTH120	VBF	VH	Tot
gg2H_0J	-0.84	-2.07	-0.17	-4.15	-0.02	-0.29	<0.01	-0.11	-0.26	-	-	4.73
gg2H_1J_ptH_0_60	0.56	2.33	-0.17	7.85	-6.82	-0.29	<0.01	-4.81	-1.86	-	-	11.86
gg2H_1J_ptH_60_120	0.56	2.33	-0.17	7.85	-6.82	-0.29	<0.01	4.99	-1.06	-	-	11.84
gg2H_1J_ptH_120_200	0.56	2.33	0.33	7.85	-6.82	-0.29	<0.01	9.89	9.94	-	-	17.63
gg2H_1J_ptH_gt200	0.56	2.33	10.23	7.85	-6.82	-0.29	<0.01	9.89	13.74	-	-	22.48
gg2H_ge2J_ptH_0_60	4.26	6.73	-0.17	4.35	18.18	-0.29	<0.01	-5.91	-1.86	-	-	21.24
gg2H_ge2J_ptH_60_120	4.26	6.73	-0.17	4.35	18.18	-0.29	<0.01	-0.21	-0.36	-	-	20.32
gg2H_ge2J_ptH_120_200	4.26	6.73	0.53	4.35	18.18	-0.29	<0.01	6.59	10.54	-	-	23.83
gg2H_ge2J_ptH_gt200	4.26	6.73	11.43	4.35	18.18	-0.29	<0.01	9.89	13.74	-	-	28.81
gg2H_VBFtopo_jet3veto	-4.64	-2.17	-0.07	-0.05	-0.02	19.71	-32.00	-1.11	1.44	-	-	37.97
gg2H_VBFtopo_jet3	-4.64	-2.17	0.13	-0.05	-0.02	19.71	23.50	0.39	2.94	-	-	31.24
VBF_qq2Hqq_VBFtopo_jet3veto	-	-	-	-	-	-	-	-	-	-0.40	-	0.40
VBF_qq2Hqq_VBFtopo_jet3	-	-	-	-	-	-	-	-	-	-0.30	-	0.30
VBF_qq2Hqq_VH2jet	-	-	-	-	-	-	-	-	-	-0.10	-	0.10
VBF_qq2Hqq_rest	-	-	-	-	-	-	-	-	-	0.20	-	0.20
VBF_qq2Hqq_pTjet1_gt200	-	-	-	-	-	-	-	-	-	0.20	-	0.20
WH_qq2Hqq_VBFtopo_jet3veto	-	-	-	-	-	-	-	-	-	-	-1.73	1.73
WH_qq2Hqq_VBFtopo_jet3	-	-	-	-	-	-	-	-	-	-	-1.63	1.63
WH_qq2Hqq_VH2jet	-	-	-	-	-	-	-	-	-	-	-0.93	0.93
WH_qq2Hqq_rest	-	-	-	-	-	-	-	-	-	-	0.27	0.27
WH_qq2Hqq_pTjet1_gt200	-	-	-	-	-	-	-	-	-	-	-4.03	4.03
qq2Hlnu_pTV_0_150	-	-	-	-	-	-	-	-	-	-	1.47	1.47
qq2Hlnu_pTV_150_250_0J	-	-	-	-	-	-	-	-	-	-	-1.73	1.73
qq2Hlnu_pTV_150_250_ge1J	-	-	-	-	-	-	-	-	-	-	-3.73	3.73
qq2Hlnu_pTV_gt250	-	-	-	-	-	-	-	-	-	-	-8.03	8.03
ZH_qq2Hqq_VBFtopo_jet3veto	-	-	-	-	-	-	-	-	-	-	-1.26	1.26
ZH_qq2Hqq_VBFtopo_jet3	-	-	-	-	-	-	-	-	-	-	-1.06	1.06
ZH_qq2Hqq_VH2jet	-	-	-	-	-	-	-	-	-	-	0.54	0.54
ZH_qq2Hqq_rest	-	-	-	-	-	-	-	-	-	-	0.24	0.24
ZH_qq2Hqq_pTjet1_gt200	-	-	-	-	-	-	-	-	-	-	-4.76	4.76
qq2Hll_pTV_0_150	-	-	-	-	-	-	-	-	-	-	0.44	0.44
qq2Hll_pTV_150_250_0J	-	-	-	-	-	-	-	-	-	-	-3.16	3.16
qq2Hll_pTV_150_250_ge1J	-	-	-	-	-	-	-	-	-	-	-3.76	3.76
qq2Hll_pTV_gt250	-	-	-	-	-	-	-	-	-	-	-6.66	6.66

Table. 5.4: Additional QCD scale uncertainties when merging STXS stage 1 bins into five production modes (ggF, VBF, WH , ZH , $t\bar{t}H$). The uncertainties are injected into $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$ and $H \rightarrow \tau\tau$ input channels. The last “Tot” column is from quadratic sum of independent sources.

STXS bin [%]	EV1	EV2	EV3	EV4	EV5	EV6	EV7	EV8	EV9	EV10	EV11	EV12	EV13	EV14	EV15	EV16	EV17	EV18	EV19	EV20	EV21	EV22	EV23	EV24	EV25	EV26	EV27	EV28	EV29	EV30	alphaS	Tot	
qq2Hllm_pTV_0_150	-0.05	0.04	<0.01	0.03	0.05	-0.02	0.00	<0.01	0.02	>-0.01	<0.01	<0.01	<0.01	-0.03	0.04	>-0.01	-0.03	0.02	<0.01	-0.03	0.00	-0.01	>-0.01	>-0.01	>-0.01	0.01	>-0.01	0.02	-0.01	0.00	0.01	0.03	0.12
qq2Hllm_pTV_150_250	0.15	-0.16	<0.01	-0.17	-0.25	0.08	0.00	<0.01	-0.08	>-0.01	<0.01	0.09	<0.01	0.17	-0.16	>-0.01	0.17	-0.08	<0.01	0.17	0.00	-0.01	>-0.01	>-0.01	>-0.01	-0.09	>-0.01	-0.08	0.09	0.00	-0.09	-0.17	0.58
qq2Hllm_pTV_g250	0.65	-0.46	-0.10	-0.37	-0.55	0.28	0.00	-0.10	-0.18	0.10	-0.10	-0.01	-0.10	0.27	-0.46	>-0.01	0.27	-0.18	-0.10	0.27	0.00	0.19	0.10	0.10	0.10	-0.09	0.10	-0.28	0.09	0.00	-0.09	-0.17	1.38
qq2Hlll_pTV_0_150	-0.07	0.20	0.02	0.33	-0.01	0.14	0.00	0.03	0.10	-0.02	0.09	0.03	-0.02	-0.08	0.02	0.06	-0.15	-0.03	0.14	0.11	0.03	-0.08	-0.03	>-0.01	0.04	-0.09	-0.02	-0.15	-0.01	>-0.01	>-0.01	0.55	
qq2Hlll_pTV_150_250	0.13	-0.20	0.02	0.13	-0.21	0.24	0.00	-0.07	>-0.01	-0.02	-0.01	0.13	-0.02	0.02	-0.18	0.06	-0.05	-0.13	0.14	0.21	0.03	0.02	0.07	>-0.01	-0.06	<0.01	-0.12	-0.05	-0.01	>-0.01	-0.21	0.62	
qq2Hlll_pTV_g250	0.63	-0.50	-0.08	-0.07	-0.51	0.54	0.00	-0.07	>-0.01	0.08	-0.11	0.03	-0.12	0.02	-0.38	0.06	0.05	-0.23	0.04	0.31	0.03	0.12	0.07	0.10	-0.06	<0.01	-0.32	-0.05	-0.01	>-0.01	-0.11	1.31	
gg2Hlll_pTV_0_150	0.13	-0.80	-0.08	-1.77	0.49	-0.96	0.00	-0.07	-0.50	0.08	-0.41	-0.27	0.08	0.42	0.12	-0.34	0.75	0.27	-0.76	-0.79	-0.17	0.32	0.07	>-0.01	-0.16	0.51	0.28	0.85	0.09	>-0.01	0.19	2.98	
gg2Hlll_pTV_150_250	0.13	-0.90	-0.08	-1.97	-0.01	-1.16	0.00	-0.17	-0.50	0.08	-0.51	-0.27	0.18	0.42	0.12	-0.34	0.85	0.37	-0.96	-0.79	-0.17	0.42	0.07	>-0.01	-0.16	0.51	0.28	0.85	0.09	>-0.01	0.19	3.28	
gg2Hlll_pTV_g250	0.03	-1.10	-0.08	-2.17	-0.61	-1.36	0.00	-0.27	-0.60	-0.02	-0.71	-0.37	0.18	0.42	0.12	-0.34	1.05	0.37	-1.16	-0.79	-0.17	0.72	0.07	>-0.01	-0.16	0.51	0.28	0.85	0.09	>-0.01	0.19	3.80	

Table. 5.5: Additional PDF uncertainties when merging STXS stage 1 bins into WH and ZH production modes. The uncertainties are only injected into the $VH \rightarrow b\bar{b}$ input channel. The last “Tot” column is from quadratic sum of independent sources.

STXS bin [%]	DeltaY_qqVH	Delta75_qqVH	Delta150_qqVH	Delta250_qqVH	DeltaY_ggZH	Delta75_ggZH	Delta150_ggZH	Delta250_ggZH	Tot
qq2Hlnu_pTV_0_150	>-0.01	-0.53	-0.21	-0.05	-	-	-	-	0.57
qq2Hlnu_pTV_150_250	>-0.01	3.27	1.29	-0.05	-	-	-	-	3.51
qq2Hlnu_pTV_gt250	>-0.01	3.27	1.29	1.35	-	-	-	-	3.77
qq2Hll_pTV_0_150	0.10	-0.53	-0.21	-0.04	-3.44	0.02	>-0.01	-0.10	3.49
qq2Hll_pTV_150_250	0.10	3.27	1.29	-0.04	-3.44	0.02	>-0.01	-0.10	4.92
qq2Hll_pTV_gt250	0.10	3.27	1.29	1.36	-3.44	0.02	>-0.01	-0.10	5.10
gg2Hll_pTV_0_150	-0.60	-0.03	-0.01	-0.04	21.56	-13.58	-6.70	-0.10	26.35
gg2Hll_pTV_150_250	-0.60	-0.03	-0.01	-0.04	21.56	26.02	13.00	-0.20	36.21
gg2Hll_pTV_gt250	-0.60	-0.03	-0.01	-0.04	21.56	26.02	13.00	13.90	38.78

Table. 5.6: Additional QCD scale uncertainties when merging STXS stage 1 bins into WH and ZH production modes. The uncertainties are only injected into the $VH \rightarrow b\bar{b}$ input channel. The last “Tot” column is from quadratic sum of independent sources.

standard VHlep stage 1 framework is different: The intermediate p_T^V bin in the $q\bar{q} \rightarrow WH/ZH$ is further split into 0 jet and ≥ 1 jet bins; There is no p_T^V boundary at 250 GeV in the $ggZH$ and the last bin is also split into 0 jet and ≥ 1 jet bins. Since the $VH \rightarrow bb$ is the most sensitive channel in measuring the VHlep STXS bins, the VHlep stage 1 framework in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow WW$ is modified to be same to the one in the $VH \rightarrow bb$: Jet bins are merged; Assume the efficiencies in the $ggZH$ p_T^V [150, 250] and [250, ∞] GeV bins are the same, then the $ggZH$ p_T^V [150, ∞] GeV bin can be split out by the cross sections of the 2 finer bins: $\mu_{>150} \cdot \sigma_{>150}^{SM} = \mu_{[150,250]} \cdot \sigma_{[150,250]}^{SM} + \mu_{>250} \cdot \sigma_{>250}^{SM}$.

5.4.3 Luminosity uncertainty splitting

The uncertainty on luminosity for the analyses based on data collected in the years 2015-2017 ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$, VH(bb), $H \rightarrow \mu\mu$) is 2.0%, and it is 2.1% for the analyses based on data collected in the years 2015-2016 (other analyses) ¹.

The correlation of the luminosity uncertainty between these two types of analyses is considered by splitting the uncertainty into correlated and uncorrelated part following the recommendation of the luminosity working group. A 1.51% uncertainty is correlated between 2015-2016 and 2015-2017 dataset. The remaining uncertainties, 1.61% from 2015-2016 and 1.27% from 2015-2017, are uncorrelated.

5.4.4 Re-implementation of branching ratio uncertainty

The values of the uncertainties are calculated by the LHC Higgs Cross section working group. There are two classes of uncertainties affecting the branching ratio: theoretical uncertainties (ΔTHU) and parametric ones ($\Delta PU(m_q)$ and $\Delta PU(\alpha_s)$). In individual channels, the branching ratio uncertainty is implemented with one nuisance parameter, corresponding to the total uncertainties calculated as:

$$\Delta(BR) = \Delta THU + \sqrt{\Delta PU(m_q)^2 + \Delta PU(\alpha_s)^2} \quad (5.13)$$

In the combination, a full model with uncertainty split into different sources summarized in Table 5.7 is implemented to replace the one NP model used in individual channels for all the workspaces, in order to properly handle the correlation between channels. Each uncertainty source in Table 5.7 is constrained by a log-normal pdf. Uncertainties below 0.1% are not considered. In addition, the α_s uncertainty from branching ratio is correlated with the one from PDF.

¹<https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics>

Channel	BR	α_s	m_b	m_c	TH bb	TH $\tau\tau$	TH $\mu\mu$	TH cc	TH gg	TH VV	TH $\gamma\gamma$	TH $Z\gamma$
$H \rightarrow bb$	5.81E-01	-0.78	0.71	-0.15	0.21	-0.03	<0.01	-0.01	-0.26	-0.12	<0.01	-0.01
$H \rightarrow \tau\tau$	6.26E-02	0.63	-0.99	-0.15	-0.29	0.47	<0.01	-0.01	-0.26	-0.12	<0.01	-0.01
$H \rightarrow \mu\mu$	2.17E-04	0.63	-0.99	-0.15	-0.29	-0.03	0.50	-0.01	-0.26	-0.12	<0.01	-0.01
$H \rightarrow cc$	2.88E-02	-0.38	-0.99	5.18	-0.29	-0.03	<0.01	0.49	-0.26	-0.12	<0.01	-0.01
$H \rightarrow gg$	8.18E-02	3.65	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	2.94	-0.12	<0.01	-0.01
$H \rightarrow \gamma\gamma$	2.27E-03	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	-0.12	1.00	-0.01
$H \rightarrow Z\gamma$	1.54E-03	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	-0.12	<0.01	4.99
$H \rightarrow VV$	2.42E-01	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	0.38	<0.01	-0.01

Table. 5.7: Summary of branching ratios of each decay channel and the corresponding branching ratio uncertainties (as percents) splitting into different sources used in the combination.

5.4.5 Scaling of Higgs boson mass

While the Higgs boson mass of 125.09 GeV from Run 1 ATLAS-CMS combination is assumed for the combination, input channels are mostly based on $m_h = 125$ GeV except for $H \rightarrow \gamma\gamma$. The production cross-sections and decay branching ratios in these channels thus need to be corrected for the 0.09 GeV mass difference. The production cross-section difference between 125 GeV and 125.09 GeV (0.1 – 0.2%) is well below the theory uncertainty and can be neglected. The branching ratio variation is also negligible except for $H \rightarrow VV$, which is close to 1%. Therefore, only the variation of $H \rightarrow VV$ branching ratio from 125 GeV to 125.09 GeV is corrected in the input workspaces. The shape variation due to the mass difference is negligible even in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel, where the signal mass resolution is not exploited in the coupling analysis.

5.5 Statistical model

5.5.1 Measurement Likelihood

The statistical methods used in this chapter also follow those of Ref. [81] and Ref. [82]. The likelihood of each input analysis a can be written as

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) = \prod_{c=1}^{N_{\text{cats}}^a} \mathcal{L}_c^a(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) \prod_{k=1}^{N_{\text{cons}}^a} \mathcal{G}(\boldsymbol{\theta}_{i_k^a}; \tilde{\boldsymbol{\theta}}_{i_k^a}) \quad (5.14)$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\theta}$ are the vectors of POIs and NPs respectively, N_{cats}^a is the number of categories in the analysis a , $\mathcal{L}_c^a$ is the likelihood function for category c , $i_1^a \dots i_{N_{\text{cons}}^a}^a$ are the indices of the constrained nuisance parameters, $\mathcal{G}$ denotes a unit Gaussian and $\tilde{\boldsymbol{\theta}}_{i_k^a}$ is the global observable corresponding to $\boldsymbol{\theta}_{i_k^a}$.

The combined likelihood is obtained by including all the categories from each input analysis, and the constraints for all constrained nuisance parameters. It can

be written as

$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) = \prod_{c=1}^{N_{\text{cats}}} \mathcal{L}_c(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) \prod_{k=1}^{N_{\text{cons}}} \mathcal{G}(\boldsymbol{\theta}_k; \tilde{\boldsymbol{\theta}}_k) \quad (5.15)$$

where $N_{\text{cats}} = \sum_a N_{\text{cats}}^a$, and N_{cons} is the overall number of constrained nuisance parameters.

The per-category likelihood in the analysis categories, for example, Equation 4.7.3 in $H \rightarrow \gamma\gamma$ analysis, is expressed in binned form as the product of Poisson distributions. It can be generally written as:

$$\mathcal{L}_c(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) = \prod_{i=1}^n \text{Pois}\left(\sum_s N_{H_s}^c(\boldsymbol{\mu}) + \sum_b N_{B_b}^c, n_i\right) \quad (5.16)$$

where n_i is the observed number of data events in each bin and $\sum_s N_{H_s}^c(\boldsymbol{\mu}) + \sum_b N_{B_b}^c$ is the signal plus background yields, similar to the unbinned case above but usually with several background components B_b .

Equation 4.10 is also used to measure the parameters of interest, based on the profile likelihood ratio [81].

In the asymptotic regime, in which the likelihood is approximately Gaussian, the value of $-2 \ln \Lambda(\boldsymbol{\nu})$ follows a χ^2 distribution with a number of degrees of freedom n equal to the dimensionality of the vector $\boldsymbol{\nu}$ [81]. This property is assumed to hold for all the results presented in the following sections. Confidence intervals for a confidence level (CL) $1-p$ are then defined as the regions with values of $-2 \ln \Lambda(\boldsymbol{\nu})$ below a threshold $F_{\chi_n^2}^{-1}(1-p)$, where $F_{\chi_n^2}^{-1}$ is the quantile function of the χ^2 distribution with n degrees of freedom.

The CL_s prescription [137] is applied when setting upper limits on parameters directly related to measured event rates such as production cross sections.

For relevant parameters of interest, a physical boundary on the parameter values is included in the statistical interpretation. For example, branching ratio parameters cannot conceptually be smaller than zero. The 95% confidence interval quoted for such parameters is then based on the profile likelihood ratio restricted to the allowed region of parameter space, using the $\tilde{t}_\mu$ test statistic of Ref. [81]. The confidence interval is defined by the standard χ^2 cutoff, which leads to some over-coverage near the boundaries.

5.5.2 Generation of Asimov dataset

Asimov dataset is used to produce expected results corresponding to the SM prediction in this note. Conventionally, it is produced using the pdf profiled to the data with signal yields fixed to the SM values (reflecting the SM assumption).

This prescription, however, does not work here for the following two reasons:

- Several types of measurements/tests (inclusive production mode cross-sections, STXS, signal strength/ κ , etc.), which differ in theory uncertainty implementation, are performed in this study. If the Asimov dataset is produced with the conventional procedure, i.e. fixing the signal yields to SM, the difference in theory uncertainty implementation, which is not trivial considering the current theory uncertainties on SM predictions are large (e.g. 5% on ggF inclusive cross-section), will lead to inconsistency in SM predictions used by these measurements/tests.
- There is a risk of biasing the background estimation by fixing the signal yield to the current theory prediction, due to its potential deviation from the real physics value.

To amend the prescription, the signal yields are profiled to data together with other nuisance parameters instead of fixed to SM when generating Asimov dataset, such that the tension between the data and the SM prediction will be mostly absorbed by the floating signal yields. The signal yields are then set back to SM prediction for producing the Asimov dataset, while the nuisance parameters remain at their profiled values. The global observables will be fixed to the profiled value of corresponding nuisance parameters later when fitting the Asimov dataset. There are three points to clarify:

- Choice of signal parameterization: to minimize the potential bias on the background estimation due to model dependence, the signal parameterization with finest granularity is always used when profiling to data. For inclusive production mode cross-sections/signal strength/ κ and BSM interpretations, the signal is split into different production modes and decay channels (Section 5.6.3). For STXS results, the corresponding STXS parameterizations are directly used (we could not use STXS parameterization for inclusive cross-section measurements due to the difference in the input channels, i.e. VBF, $H \rightarrow b\bar{b}$ is missing in STXS).
- Even with signal yields profiled to data, there will still be small difference between Asimov dataset generated for different set of measurements/tests due to difference in signal parameterization and theory uncertainty implementations. These difference are small, and justified for the reason of ensuring good closure with SM prediction.
- The combined workspace is used to generate Asimov dataset.

5.5.3 Compatibility with the Standard Model

The compatibility with the Standard Model is quantified using the test statistic $\lambda_{\text{SM}} = -2 \ln \Lambda(\boldsymbol{\nu} = \boldsymbol{\nu}_{\text{SM}})$, where $\boldsymbol{\nu}_{\text{SM}}$ are the Standard Model values of the parameters of interest. A p -value² p_{SM} for the compatibility is computed in the asymptotic approximation as $p_{\text{SM}} = 1 - F_{\chi_n^2}(\lambda_{\text{SM}})$, with n equal to the number of free parameters of interest. For the cross section and branching ratio measurements in this paper, this definition does not account for the uncertainties on the SM values used as reference and may therefore lead to an underestimate of the compatibility with the SM.

5.6 Combined measurements of signal strength, production cross sections and branching ratios

5.6.1 Global signal strength

This subsection discusses the measurements of the a global strength parameter μ applied to all measured signal yields, which is the ratio of an observed yield to its SM expectation as shown in Equation 4.1. The uncertainties on the SM predictions are included as nuisance parameters in the measurement of the signal strength modifiers, following the introduction in Section 5.5.

$$\mu = 1.11_{-0.08}^{+0.09} = 1.11 \pm 0.05 (\text{stat.})_{-0.04}^{+0.05} (\text{exp.})_{-0.04}^{+0.05} (\text{sig. th.}) \pm 0.03 (\text{bkg. th.})$$

where a the total uncertainty is divided into statistical uncertainties, experimental systematic uncertainties, and theory uncertainties on signal and background modeling.

Figure 5.1 shows the value of $-2 \ln \Lambda(\mu)$ as a function of μ , for the full likelihood and the curves showing the error decompositions.

The compatibility with the SM prediction corresponds to a p -value of $p_{\text{SM}} = 18\%$ computed by using the methodology described in Section 5.5 with one degree of freedom.

The leading uncertainties of the global signal strength measurement are shown in Table 5.8. The theory modeling of the signal and background processes in Monte-carlo simulation are the dominant uncertainties. Uncertainties relate to the luminosity measurement; photons and electron selection efficiencies, energy scale and energy resolution also play important roles in the measurement.

²The p -value is defined as the probability to obtain a value of the test statistic that is at least as high as the observed value under the hypothesis that is being tested.

Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ -lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

Table. 5.8: Summary of the relative uncertainties $\Delta\mu/\mu$ in the measurement of the combined global signal strength μ . “MC stat.” refers to uncertainties due to the limited number of simulated events. “Other” refers to the combined effect of the sources of experimental systematic uncertainty not explicitly listed in the table.

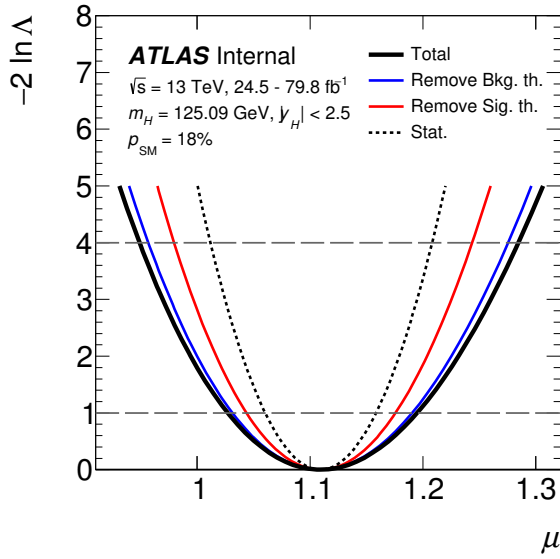


Fig. 5.1: Value of $-2 \ln \Lambda(\mu)$ as a function of μ with all systematic uncertainties included (solid black line), with theory uncertainties on background processes removed (solid blue line), with the additionally removing theory uncertainties on the signal process (solid red line) and all systematic uncertainties (dotted black line).

5.6.2 Production cross sections

The major Higgs boson production modes (Section 1.2) are studied, including ggF, VBF, WH , ZH and $t\bar{t}H+tH$. In this measurement, the POIs are the cross-sections for those main Higgs production modes. The measurement is performed assuming SM values for the branching ratios of all the decay channels of the Higgs boson. The combination assumes the relative fractions of each component to be as in the SM when cases where several processes are combined, with theory uncertainties assigned. The small contribution from $b\bar{b}H$ is grouped with ggF. Cross sections are reported in the region $|y_H| < 2.5$ of the Higgs boson rapidity y_H .

Figure 5.2 and Table 5.9 show the result. Table 5.10 summarizes The leading sources of uncertainty on the production cross section measurements. The correlations in this measurement are shown in Figure 5.3.

The correlation between the ggF and VBF processes is -15% , indicating a good performance in developing ggF and VBF-enriched categories. The consistency between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 76\%$, computed using the procedure outlined in Section 5.5 with 5 degrees of freedom.

Figure 5.4 shows the observed likelihood contours in the plane of σ_{ggF} ver-

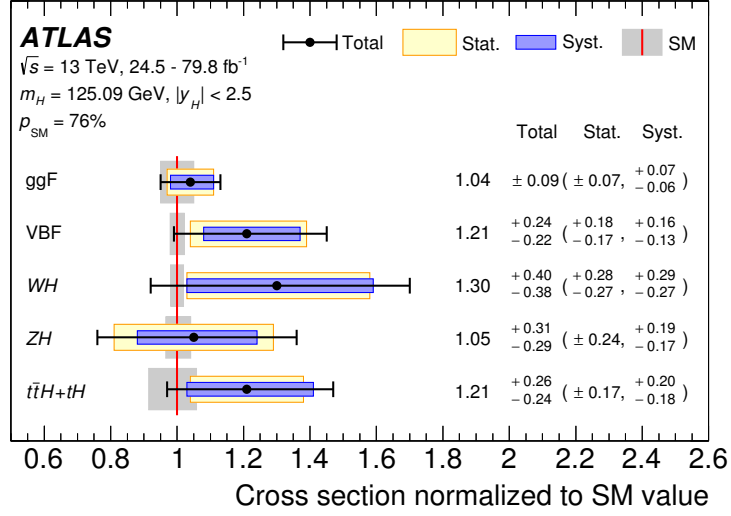


Fig. 5.2: Cross sections for ggF, VBF, WH , ZH and $t\bar{t}H+tH$ normalized to their SM predictions. The black error bars, yellow boxes and blue boxes show the total, statistical, and systematic uncertainties, respectively. The gray bands show the theory uncertainties in the predicted cross sections.

Process ($ y_H < 2.5$)	Value [pb]	Uncertainty [pb]					SM pred. [pb]	Significance obs. (exp.)
		Total	Stat.	Exp.	Sig. th.	Bkg. th.		
ggF	46.5	±4.0	±3.1	±2.2	±0.9	±1.3	44.7 ± 2.2	-
VBF	4.25	+0.84 -0.77	+0.63 -0.60	+0.35 -0.32	+0.42 -0.32	+0.14 -0.11	3.515 ± 0.075	6.5 (5.3)
WH	1.57	+0.48 -0.46	+0.34 -0.33	+0.25 -0.24	+0.11 -0.07	±0.20	1.204 ± 0.024	3.5 (2.7)
ZH	0.84	+0.25 -0.23	±0.19	±0.09	+0.07 -0.04	±0.10	0.797 ^{+0.033} _{-0.026}	3.6 (3.6)
t $\bar{t}H+tH$	0.71	+0.15 -0.14	±0.10	±0.07	+0.05 -0.04	+0.08 -0.07	0.586 ^{+0.034} _{-0.049}	5.8 (5.4)

Table. 5.9: Best-fit values and decomposed uncertainties for the production cross sections of the Higgs boson. SM predictions [3] are shown for the cross section of each production process. The observed (obs.) and expected (exp.) significances of the observed signals relative to the no-signal hypothesis are also shown for all processes except ggF, which was observed in Run 1.

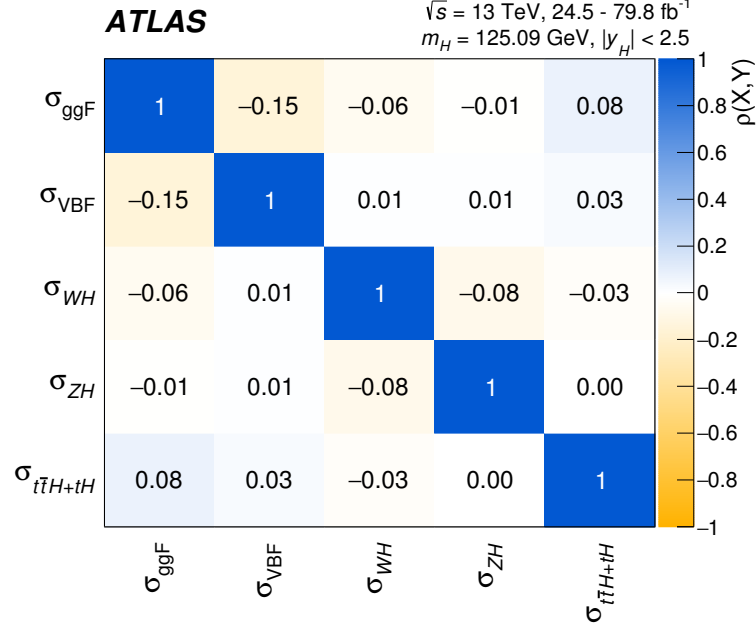


Fig. 5.3: Correlation matrix for the measurement of production cross sections of the Higgs boson.

Uncertainty source	$\frac{\Delta\sigma_{ggF}}{\sigma_{ggF}} [\%]$	$\frac{\Delta\sigma_{VBF}}{\sigma_{VBF}} [\%]$	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}} [\%]$	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} [\%]$	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}} [\%]$
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, E_T^{miss}	0.9	5.4	3.0	3.3	4.0
Flavour tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ -lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21

Table. 5.10: Summary of the uncertainties in the production cross section measurements.

sus σ_{VBF} from individual channels and the combined fit, together with the SM prediction.

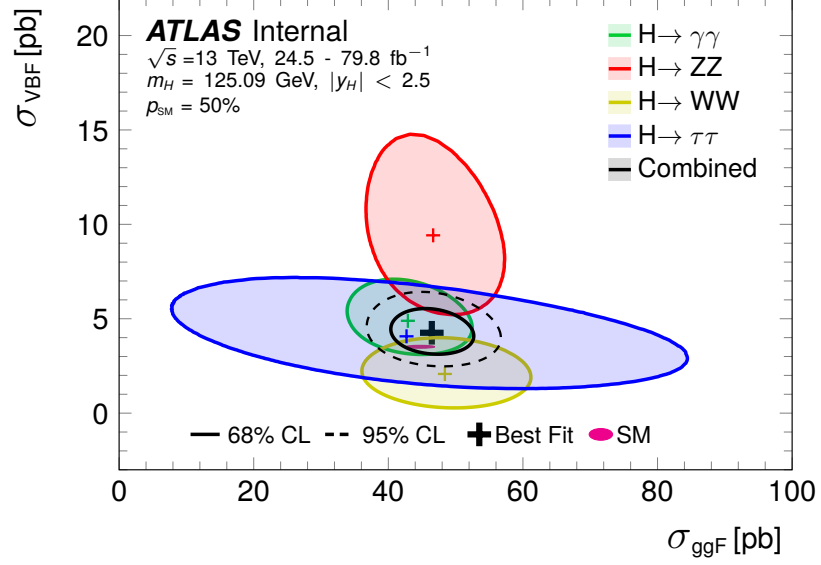


Fig. 5.4: Observed likelihood contours in the plane of σ_{VBF} versus σ_{ggF} from individual channels and the combined fit.

All the major production modes have reached observed significances above 5σ . For the WH and ZH modes, these are 3.5σ (2.7σ) and 3.6σ (3.6σ), respectively. The single VH process with combining WH and ZH production by the ratio of the SM predicted value gives an observed (expected) significance for this process of 5.3σ (4.7σ). For the $t\bar{t}H + tH$ production, the observed (expected) significance is 5.8σ (5.4σ). For the VBF process, the observed (expected) significance is 6.5σ (5.3σ). It is the first single-experiment observation of the VBF production mode.

5.6.3 Products of production cross sections and branching ratios

The major production modes ggF , VBF , VH and $t\bar{t}H$ cross sections are measured in each individual decay channel with a sufficient sensitivity. The WH and ZH are considered together as a single VH process as they cannot be reliably determined in all decay channels except $H \rightarrow b\bar{b}$. For the $t\bar{t}H$ production mode, we merge $H \rightarrow WW^{(*)}$ and $H \rightarrow ZZ^{(*)}$ channels since there is no sensitivity to separate the two. Similarly, the contribution from $H \rightarrow b\bar{b}$ to the ggF production mode is fixed to its SM prediction. In addition, the $b\bar{b}H$, tH and $ggZH$ contributions are included in the ggF , $t\bar{t}H$ and VH measurements, respectively.

The results are shown in Figure 5.5 and Table 5.11. Figure 5.6 shows the correlation matrix. Due to the cross-contamination, the relatively large correlations are found between the $t\bar{t}H$, $H \rightarrow VV^*$ and $t\bar{t}H$, $H \rightarrow \tau\tau$ processes, and between the ggF , $H \rightarrow \tau\tau$ and VBF , $H \rightarrow \tau\tau$ processes. The compatibility between

the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 71\%$, computed using the procedure described in Section 5.5 with 16 degrees of freedom.

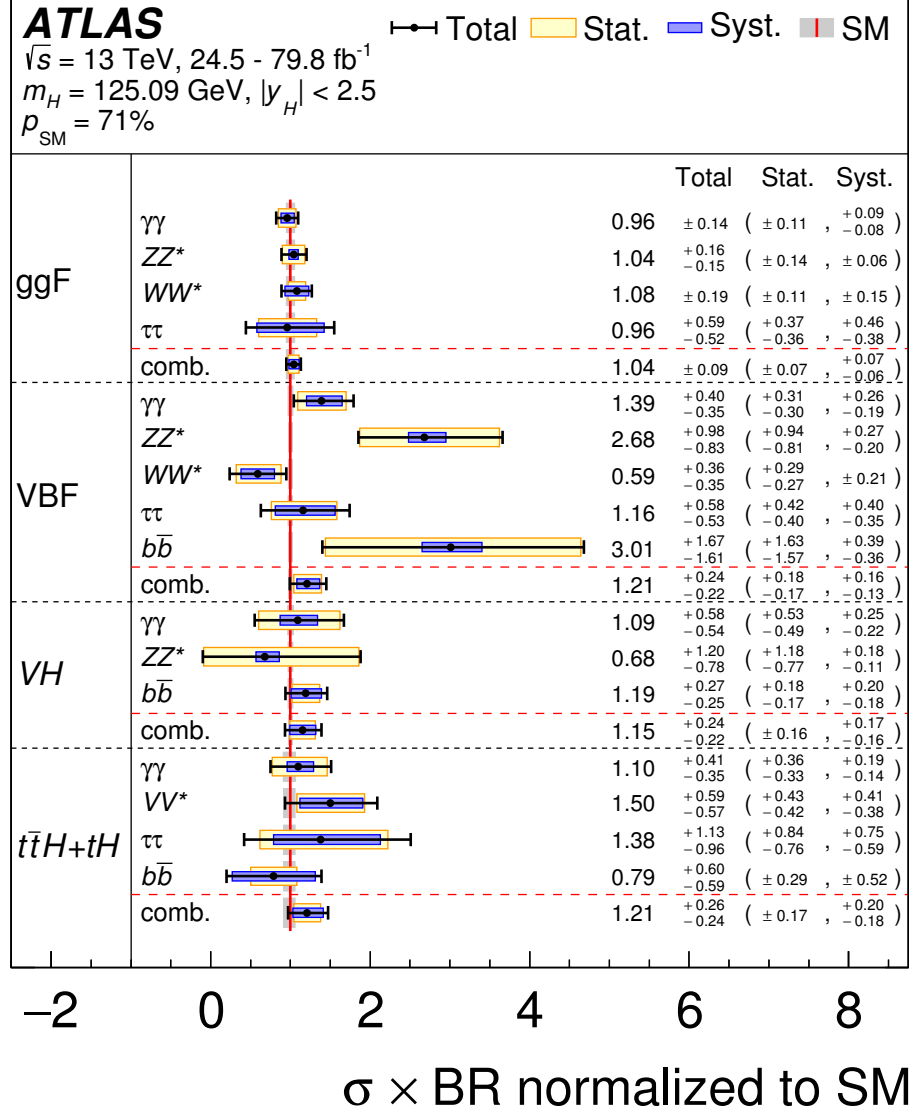


Fig. 5.5: Cross sections times branching fraction for ggF, VBF, VH and $t\bar{t}H+tH$ production in each relevant decay mode, normalized to their SM predictions shown in Table 5.11.

Process ($ y_H < 2.5$)	Value [fb]	Uncertainty [fb]					SM pred. [fb]
		Total	Stat.	Exp.	Sig. th.	Bkg. th.	
ggF, $H \rightarrow \gamma\gamma$	97	± 14	± 11	± 8	± 2	$^{+2}_{-1}$	101.5 ± 5.3
ggF, $H \rightarrow ZZ^{(*)}$	1230	$^{+190}_{-180}$	± 170	± 60	± 20	± 20	1181 ± 61
ggF, $H \rightarrow WW^{(*)}$	10400	± 1800	± 1100	± 1100	± 380	$^{+960}_{-870}$	9600 ± 500
ggF, $H \rightarrow \tau\tau$	2700	$^{+1700}_{-1500}$	± 1000	± 920	$^{+810}_{-310}$	$^{+390}_{-420}$	2800 ± 140
VBF, $H \rightarrow \gamma\gamma$	11.1	$^{+3.2}_{-2.8}$	$^{+2.5}_{-2.4}$	$^{+1.4}_{-1.0}$	$^{+1.5}_{-1.1}$	$^{+0.3}_{-0.2}$	7.98 ± 0.21
VBF, $H \rightarrow ZZ^{(*)}$	249	$^{+91}_{-77}$	$^{+87}_{-75}$	$^{+16}_{-11}$	$^{+17}_{-12}$	$^{+9}_{-7}$	92.8 ± 2.3
VBF, $H \rightarrow WW^{(*)}$	450	$^{+270}_{-260}$	$^{+220}_{-200}$	$^{+120}_{-130}$	$^{+80}_{-70}$	$^{+70}_{-80}$	756 ± 19
VBF, $H \rightarrow \tau\tau$	260	$^{+130}_{-120}$	± 90	$^{+80}_{-70}$	$^{+30}_{-10}$	$^{+30}_{-20}$	220 ± 6
VBF, $H \rightarrow b\bar{b}$	6100	$^{+3400}_{-3300}$	$^{+3300}_{-3200}$	$^{+700}_{-600}$	± 300	± 300	2040 ± 50
VH , $H \rightarrow \gamma\gamma$	5.0	$^{+2.6}_{-2.5}$	$^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	± 0.5	± 0.1	$4.54^{+0.13}_{-0.12}$
VH , $H \rightarrow ZZ^{(*)}$	36	$^{+63}_{-41}$	$^{+62}_{-41}$	$^{+5}_{-4}$	$^{+6}_{-4}$	$^{+4}_{-2}$	52.8 ± 1.4
VH , $H \rightarrow b\bar{b}$	1380	$^{+310}_{-290}$	$^{+210}_{-200}$	± 150	$^{+120}_{-80}$	± 140	1162^{+31}_{-29}
$t\bar{t}H+tH$, $H \rightarrow \gamma\gamma$	1.46	$^{+0.55}_{-0.47}$	$^{+0.48}_{-0.44}$	$^{+0.19}_{-0.15}$	$^{+0.17}_{-0.11}$	± 0.03	$1.33^{+0.08}_{-0.11}$
$t\bar{t}H+tH$, $H \rightarrow VV^*$	212	$^{+84}_{-81}$	$^{+61}_{-59}$	$^{+47}_{-44}$	$^{+17}_{-10}$	$^{+31}_{-30}$	142^{+8}_{-12}
$t\bar{t}H+tH$, $H \rightarrow \tau\tau$	51	$^{+41}_{-35}$	$^{+31}_{-28}$	$^{+26}_{-21}$	$^{+6}_{-4}$	$^{+8}_{-6}$	$36.7^{+2.2}_{-3.1}$
$t\bar{t}H+tH$, $H \rightarrow b\bar{b}$	270	± 200	± 100	± 80	$^{+40}_{-10}$	$^{+150}_{-160}$	341^{+20}_{-29}

Table. 5.11: Best-fit values and uncertainties for the production cross sections times branching ratios of the Higgs boson, for the combinations in which sufficient sensitivity is provided by the input analyses. The total uncertainties are decomposed into components for data statistics (Stat.), experimental systematic uncertainties (Exp.), and theory uncertainties in the modeling of the signal (Sig. th.) and background (Bkg. th.) processes.

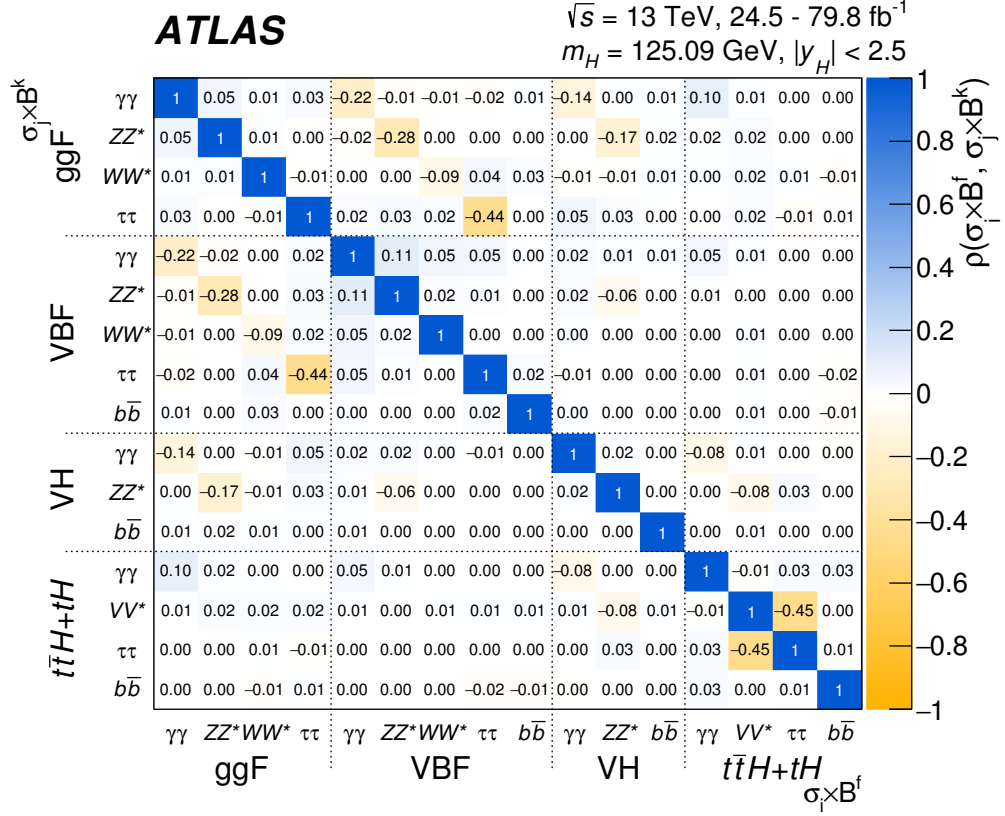


Fig. 5.6: Correlation matrix for the measured values of the production cross sections times branching ratios of the Higgs boson

5.6.4 Ratios of cross sections and branching fractions

In Section 5.6.3, products of $(\sigma \times B)_{if}$ are measured. The reference process $gg \rightarrow H \rightarrow ZZ^*$ (σ_{ggF}^{ZZ}) can be used to decompose the production and decay. $(\sigma \times B)_{if}$ can be expressed as ratios of production cross sections to that of ggF , σ_i/σ_{ggF} , and ratios of branching fractions to that of $H \rightarrow ZZ^{(*)}$, B_f/B_{ZZ} :

$$(\sigma \times B)_{if} = \sigma_{ggF}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{ggF}} \right) \cdot \left(\frac{B_f}{B_{ZZ}} \right), \quad (5.17)$$

Figure 5.7 and Table 5.12 summarize the results. The compatibility between the measurements and the SM predictions corresponds to a p -value of $p_{SM} = 93\%$, computed using the procedure outlined in Section 5.5 with 9 degrees of freedom.

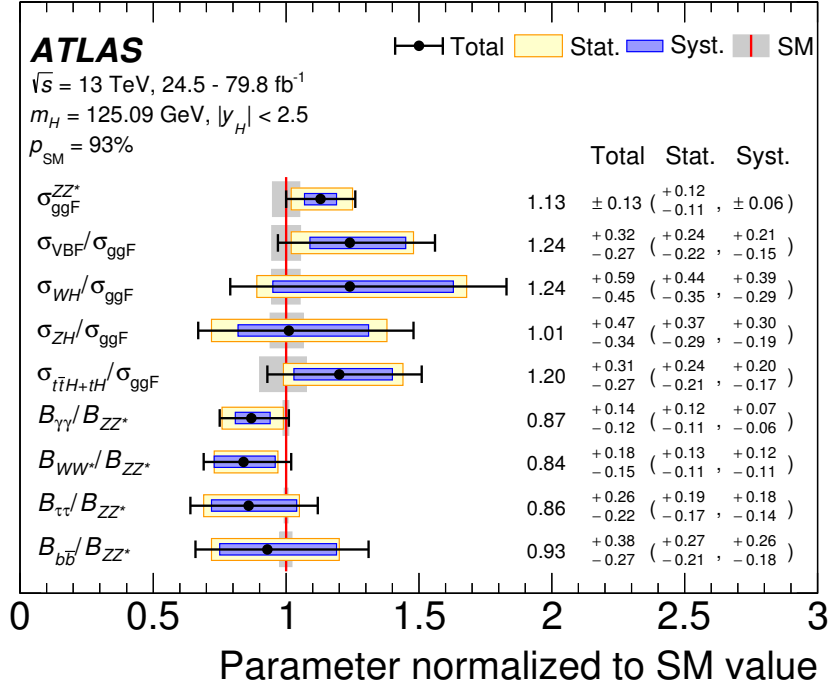


Fig. 5.7: Results of a simultaneous fit for those ratio parameters: σ_{ggF}^{ZZ} , $\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$, $\sigma_{WH}/\sigma_{\text{ggF}}$, $\sigma_{ZH}/\sigma_{\text{ggF}}$, $\sigma_{t\bar{t}H+tH}/\sigma_{\text{ggF}}$, $B_{\gamma\gamma}/B_{ZZ}$, B_{WW}/B_{ZZ} , $B_{\tau\tau}/B_{ZZ}$, and B_{bb}/B_{ZZ} .

Quantity	Value	Uncertainty					SM prediction
		Total	Stat.	Exp.	Sig. th.	Bkg. th.	
σ_{ggF}^{ZZ} [pb]	1.33	± 0.15	$+0.14$ -0.13	± 0.06	± 0.02	± 0.04	1.181 ± 0.061
$\sigma_{\text{VBF}}/\sigma_{\text{ggF}}$	0.097	$+0.025$ -0.021	$+0.019$ -0.017	$+0.010$ -0.008	$+0.011$ -0.008	$+0.006$ -0.005	0.0786 ± 0.0043
$\sigma_{WH}/\sigma_{\text{ggF}}$	0.034	$+0.016$ -0.012	$+0.012$ -0.009	$+0.008$ -0.006	$+0.003$ -0.002	$+0.007$ -0.005	$0.0269^{+0.0014}_{-0.0015}$
$\sigma_{ZH}/\sigma_{\text{ggF}}$	0.0180	$+0.0084$ -0.0062	$+0.0066$ -0.0052	$+0.0034$ -0.0021	$+0.0016$ -0.0009	$+0.0037$ -0.0025	$0.0178^{+0.0011}_{-0.0010}$
$\sigma_{t\bar{t}H+tH}/\sigma_{\text{ggF}}$	0.0157	$+0.0041$ -0.0035	$+0.0031$ -0.0029	$+0.0020$ -0.0017	$+0.0012$ -0.0008	$+0.0013$ -0.0012	$0.0131^{+0.0010}_{-0.0013}$
$B_{\gamma\gamma}/B_{ZZ}$	0.075	$+0.012$ -0.010	$+0.010$ -0.009	$+0.006$ -0.005	$+0.002$ -0.001	± 0.002	0.0860 ± 0.0010
B_{WW}/B_{ZZ}	6.8	$+1.5$ -1.2	$+1.1$ -0.9	$+0.8$ -0.7	± 0.2	$+0.6$ -0.5	$8.15 \pm < 0.01$
$B_{\tau\tau}/B_{ZZ}$	2.04	$+0.62$ -0.52	$+0.45$ -0.40	$+0.36$ -0.31	$+0.17$ -0.09	$+0.12$ -0.09	2.369 ± 0.017
B_{bb}/B_{ZZ}	20.5	$+8.4$ -6.2	$+6.2$ -4.6	$+3.7$ -2.4	$+1.3$ -0.9	$+4.2$ -2.9	22.00 ± 0.51

Table. 5.12: Best-fit values and uncertainties for σ_{ggF}^{ZZ} , together with ratios of production cross sections normalized to σ_{ggF} , and ratios of branching fractions normalized to B_{ZZ} . The total uncertainties are decomposed into components for data statistics (Stat.), experimental systematic uncertainties (Exp.), and theory uncertainties in the modeling of the signal (Sig. th.) and background (Bkg. th.) processes.

5.7 Combined measurements of simplified template cross sections

5.7.1 Simplified template cross section merging scheme

The Stage 1 splitting of the STXS framework [3] described in Section 1.3 are performed in this combined measurement.

A reduced splitting is adopted due to the limited sensitivity to the cross section in some bins of the Stage 1 scheme caused by the limited data statistics. The definition of the merged groups of Stage 1 bins for each process are as follows:

- $gg \rightarrow H$ is separated into six regions initially defined by 0, 1 and 2 or more associated jets. Regions with at least one jet are further divided by the Higgs boson transverse momentum p_T^H : $p_T^H < 60$ GeV, $60 \text{ GeV} \leq p_T^H < 120$ GeV and $120 \text{ GeV} \leq p_T^H < 200$ GeV. An additional region is defined for events with one or more jets and with the highest $p_T^H \geq 200$ GeV, providing sensitivity to the potential BSM effects at high momentum transfer.
- $qq \rightarrow Hqq$ is divided into three regions, including all $qq \rightarrow Hqq$ production –not only VBF but also VH with hadronic V decays. At Stage 1 the two components are however separated through events kinematics into a high- p_T category with leading jet $p_T^j \geq 200$ GeV and sensitive to the potential BSM effects. A VH -like categories is then defined with $p_T^j < 200$ GeV and the presence of two jets with an invariant mass m_{jj} in the range $60 \leq m_{jj} < 120$ GeV. The last one is the remaining events, including events with VBF-like topology, containing two jets with $m_{jj} \geq 400$ GeV and a pseudorapidity difference $|\Delta\eta_{jj}| \geq 2.8$, and also events don't meet requirements of the above categories.
- $V(\text{lep})H$ contains two processes $qq \rightarrow WH$ and $pp \rightarrow ZH$, the latter including both quark-initiated and gluon-initiated production. The transverse momentum of the W or Z , p_T^V , are used to further split events. For the $qq \rightarrow WH$ process two bins are defined for $p_T^V \leq 250$ GeV and $p_T^V > 250$ GeV, while for $pp \rightarrow ZH$ three bins are defined for $p_T^V < 150$ GeV, $150 \text{ GeV} \leq p_T^V < 250$ GeV and $p_T^V \geq 250$ GeV.

Figure 5.8 shows the merging scheme applied in this measurement.

The $H \rightarrow \gamma\gamma$ analysis provides the leading contributions to all $gg \rightarrow H$ regions except 0-jet, which is dominated by the $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ analysis. In the $qq \rightarrow Hqq$ sector, the leading sensitivities are still given by the $H \rightarrow \gamma\gamma$ analysis. The only exception is the $p_T^j > 200$ GeV region, where $H \rightarrow \tau\tau$ dominates the sensitivity. The major sensitivity in $V(\text{lep})H$ regions is given by the VH , $H \rightarrow b\bar{b}$ analysis. The $t\bar{t}H+tH$ is dominated by the $H \rightarrow \gamma\gamma$ and $t\bar{t}H$ multilepton analyses.

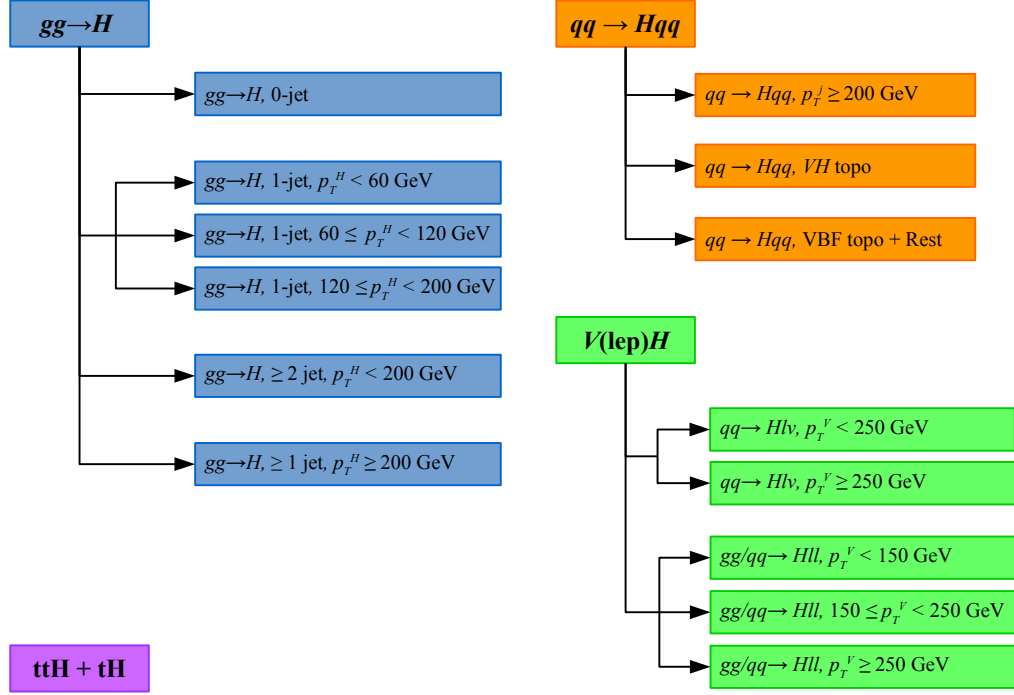


Fig. 5.8: Definition of the STXS merging scheme. The $b\bar{b}H$ production mode is considered as part of $gg \rightarrow H$.

The parameters of interest of the form $(\sigma \times B)_{if}$ denoting the cross section times branching ratio in STXS region i and decay channel f . The acceptance factors $(\epsilon \times A)_{if}^k$ for each analysis category k are determined from SM Higgs boson production processes, modeled using the samples described in Section 5.2, and act as templates in the fits of the STXS cross sections to the data. The dependence on the theory assumptions is reduced compared to the measurement of the total cross sections in each production mode, since the $(\epsilon \times A)_{if}^k$ are computed over smaller regions. Assumptions on the kinematics within a given STXS region lead to some model-dependence, which reduced further using a finer splitting of the phase space where this is justified by the experimental precision.

5.7.2 Results

Giving that it is precisely measured and exhibits small systematic uncertainties, the $H \rightarrow ZZ^{(*)}$ decay is chosen to be the benchmark process in all fitted parameters for the combined STXS measurements. The production are expressed as the Higgs boson production in STXS region i times the branching fraction for the $H \rightarrow ZZ^{(*)}$ decay, $(\sigma \times B)_{i,ZZ}$, and the branching fractions are expressed as B_f/B_{ZZ} for the other final states f .

$$(\sigma \times \text{B})_{if} = (\sigma \times \text{B})_{i,ZZ} \cdot \left(\frac{\text{B}_f}{\text{B}_{ZZ}} \right). \quad (5.18)$$

The normalized-to-SM results are shown in Figure 5.9, the cross-section number results are summarized in Figure 5.10 and Table 5.13. The correlations between the measured parameters are shown in Figure 5.11.

The observed upper limits at 95% CL on the cross sections in the $qq \rightarrow Hqq$, $(V \rightarrow q\bar{q})H$ and $qq \rightarrow Hqq$, $p_T^j \geq 200$ GeV bins are found to be 1.45 pb and 0.59 pb, respectively. The corresponding expected upper limits are 1.53 pb and 0.80 pb, respectively.

The 19-D compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 88\%$.

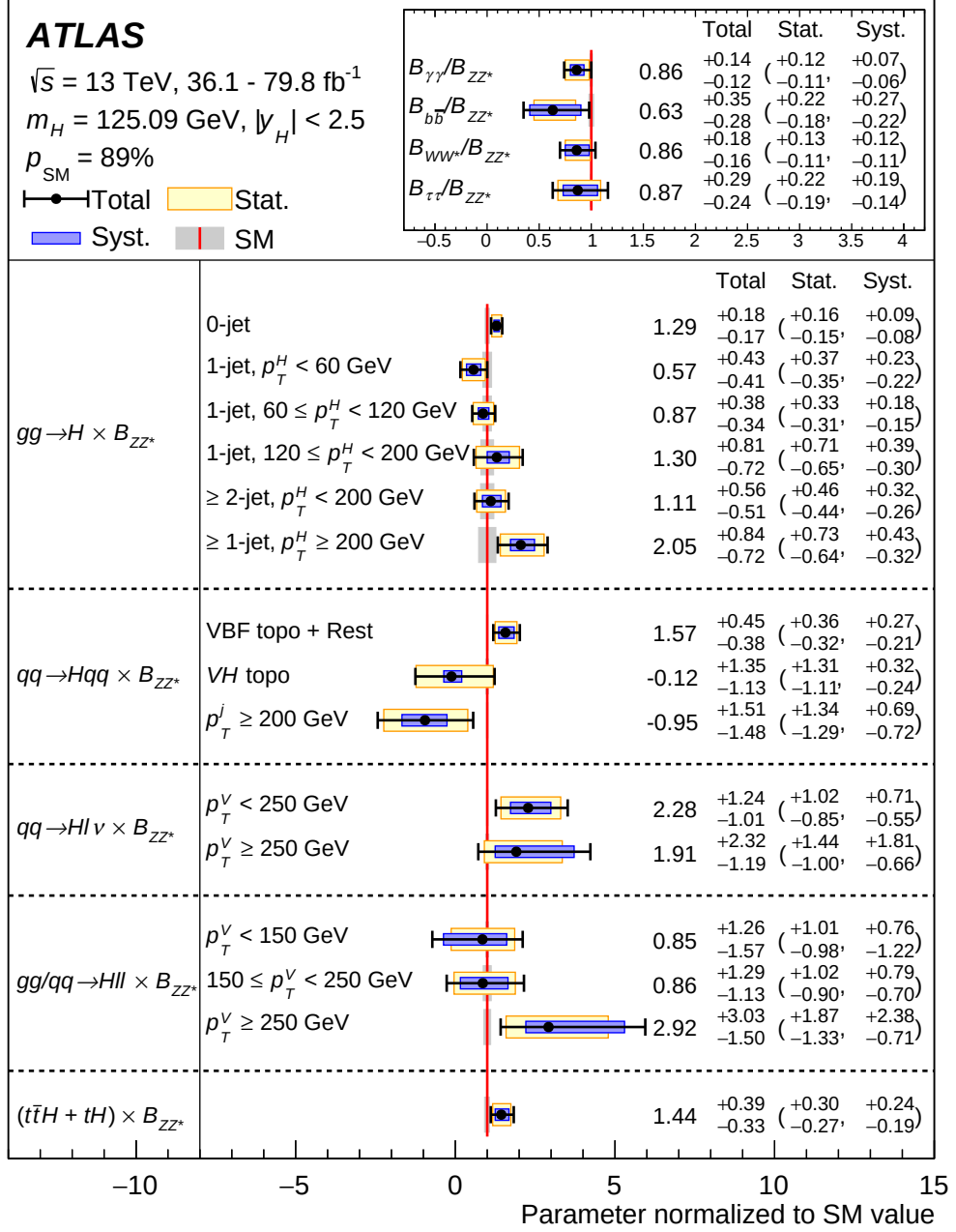


Fig. 5.9: Best-fit values and uncertainties for the cross sections in each measurement region and of the ratios of branching fractions B_f/B_{ZZ} , normalized to the SM predictions for the various parameters.

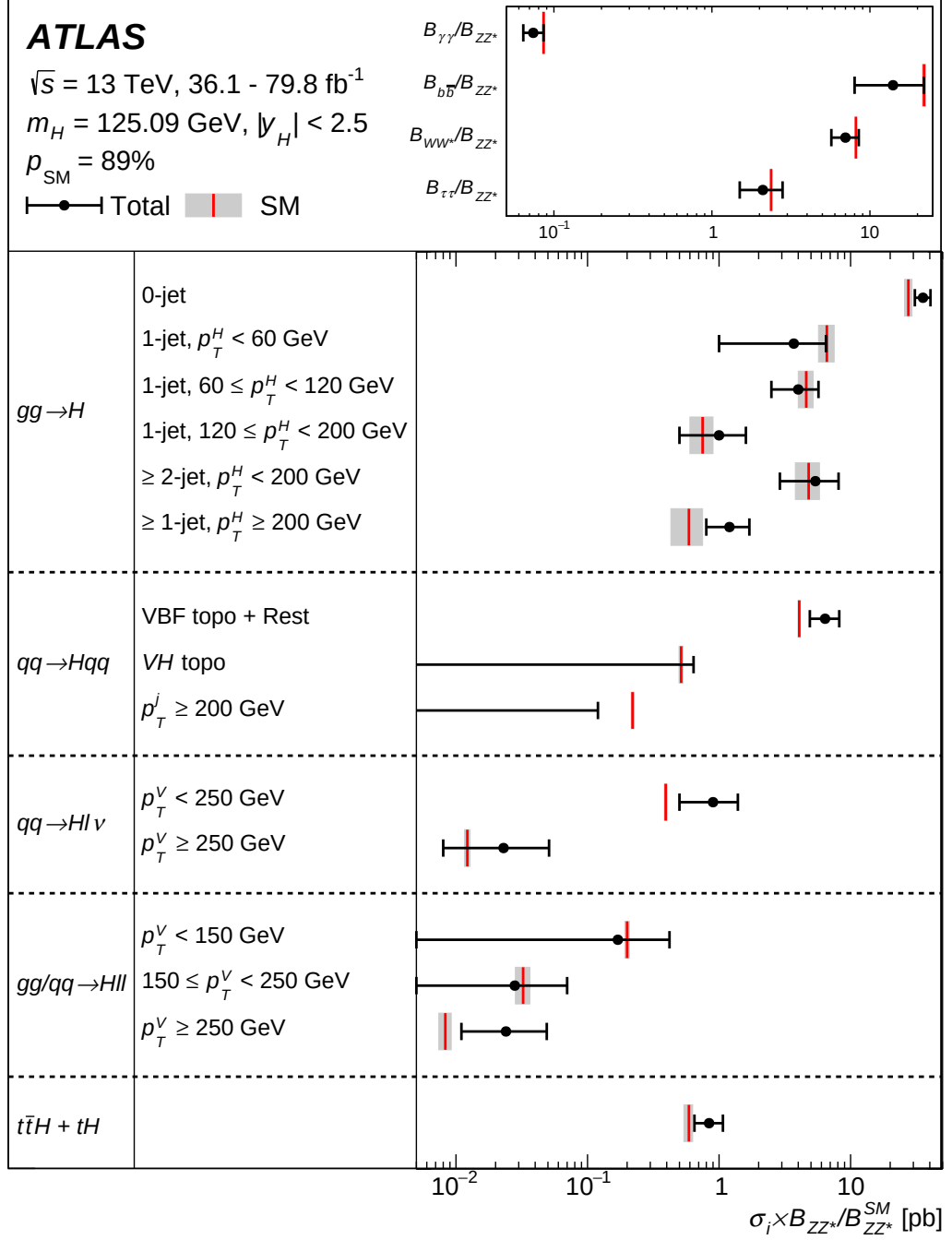


Fig. 5.10: Best-fit values and uncertainties for the cross sections in each measurement region and of the ratios of branching fractions B_f/B_{ZZ^*} .

Measurement region $\left((\sigma_i \times B_{ZZ})/B_{ZZ}^{\text{SM}}\right)$	Result [pb]	Uncertainty [pb]			SM prediction [pb]
		Total	Stat.	Syst.	
$gg \rightarrow H$, 0-jet	35.5	$+5.0$ -4.7	$+4.4$ -4.1	$+2.5$ -2.2	27.5 ± 1.8
$gg \rightarrow H$, 1-jet, $p_T^H < 60$ GeV	3.7	$+2.8$ -2.7	$+2.4$ -2.3	$+1.5$ -1.4	6.6 ± 0.9
$gg \rightarrow H$, 1-jet, $60 \leq p_T^H < 120$ GeV	4.0	$+1.7$ -1.5	$+1.5$ -1.4	$+0.8$ -0.7	4.6 ± 0.6
$gg \rightarrow H$, 1-jet, $120 \leq p_T^H < 200$ GeV	1.0	$+0.6$ -0.5	± 0.5	$+0.3$ -0.2	0.75 ± 0.15
$gg \rightarrow H$, ≥ 1 -jet, $p_T^H \geq 200$ GeV	1.2	$+0.5$ -0.4	± 0.4	$+0.3$ -0.2	0.59 ± 0.16
$gg \rightarrow H$, ≥ 2 -jet, $p_T^H < 200$ GeV	5.4	$+2.7$ -2.5	$+2.2$ -2.1	$+1.5$ -1.3	4.8 ± 1.0
$qq \rightarrow Hqq$, $qq' \rightarrow qq'H$ topo + Rest	6.4	$+1.8$ -1.5	$+1.5$ -1.3	$+1.1$ -0.9	4.07 ± 0.09
$qq \rightarrow Hqq$, $q\bar{q} \rightarrow WH/ZH$ topo	-0.06	$+0.70$ -0.58	$+0.68$ -0.57	$+0.16$ -0.12	0.515 ± 0.019
$qq \rightarrow Hqq$, $p_T^j \geq 200$ GeV	-0.21	± 0.33	$+0.29$ -0.28	$+0.15$ -0.16	0.220 ± 0.005
$qq \rightarrow H\ell\nu$, $p_T^V < 250$ GeV	0.90	$+0.49$ -0.40	$+0.40$ -0.33	$+0.28$ -0.22	0.393 ± 0.009
$qq \rightarrow H\ell\nu$, $p_T^V \geq 250$ GeV	0.023	$+0.028$ -0.015	$+0.018$ -0.012	$+0.022$ -0.008	0.0122 ± 0.0006
$gg/qq \rightarrow H\ell\ell$, $p_T^V < 150$ GeV	0.17	$+0.25$ -0.31	± 0.20	$+0.15$ -0.24	0.200 ± 0.008
$gg/qq \rightarrow H\ell\ell$, $150 \leq p_T^V < 250$ GeV	0.028	$+0.042$ -0.037	$+0.033$ -0.029	$+0.026$ -0.023	0.0324 ± 0.0041
$gg/qq \rightarrow H\ell\ell$, $p_T^V \geq 250$ GeV	0.024	$+0.025$ -0.013	$+0.016$ -0.011	$+0.020$ -0.006	0.0083 ± 0.0009
$q\bar{q}/gg \rightarrow t\bar{t}H + tH$	0.84	$+0.23$ -0.19	$+0.18$ -0.16	$+0.14$ -0.11	$0.59^{+0.04}_{-0.05}$
Branching fraction ratio	Result	Uncertainty			SM prediction
		Total	Stat.	Syst.	
$B_{\gamma\gamma}/B_{ZZ}$	0.074	$+0.012$ -0.010	$+0.010$ -0.009	$+0.006$ -0.005	0.0860 ± 0.0010
$B_{b\bar{b}}/B_{ZZ}$	14	$+8$ -6	$+5$ -4	$+6$ -5	22.0 ± 0.5
B_{WW}/B_{ZZ}	7.0	$+1.5$ -1.3	$+1.1$ -0.9	$+1.0$ -0.9	8.15 ± 0.01
$B_{\tau\tau}/B_{ZZ}$	2.1	$+0.7$ -0.6	± 0.5	$+0.5$ -0.3	2.37 ± 0.02

Table. 5.13: Best-fit values and uncertainties for the cross sections in each measurement region, and of the ratios of branching fractions B_f/B_{ZZ} . The total uncertainties are decomposed into components for data statistics (Stat.) and systematic uncertainties (Syst.). The SM predictions [3] are also shown for each quantity with their total uncertainties.

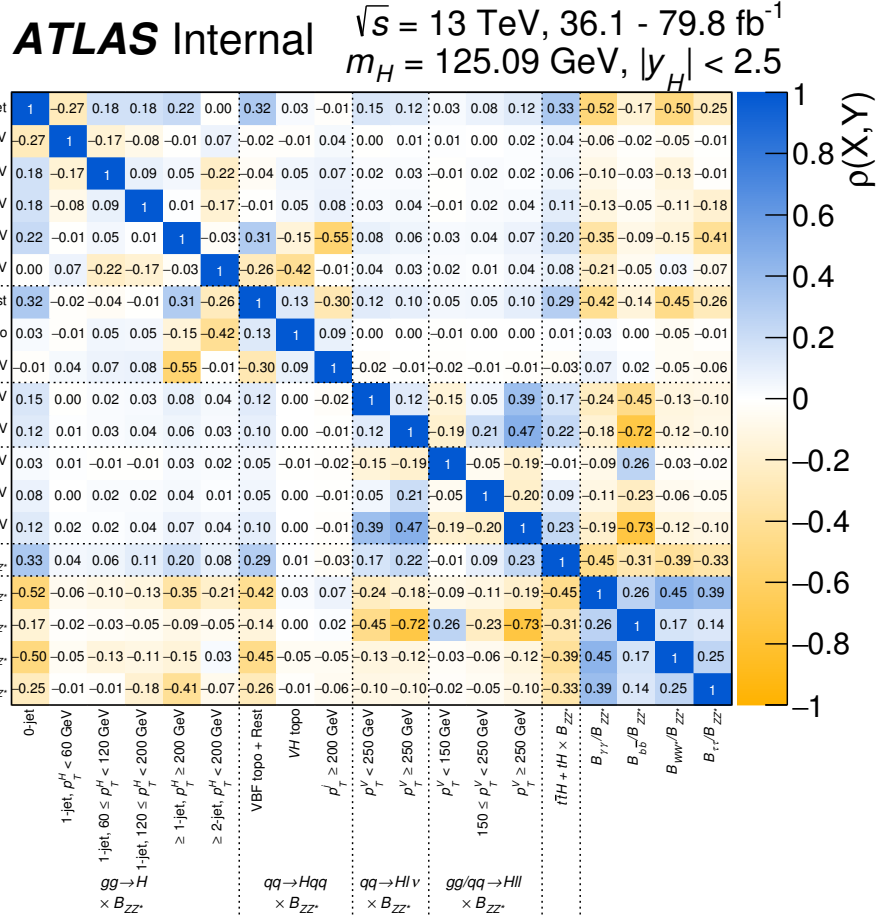


Fig. 5.11: Correlation matrix for the measured values of the simplified template cross sections and ratios of branching fractions.

5.8 Interpretation of results in the κ framework

Following the tree-level-motivated framework and benchmark models (Ref. [2], Section 1.4), measurements of Higgs boson coupling-strength modifiers κ_j are implemented in this combined measurement, to provide a consistent treatment of coupling strengths in Higgs boson production and decay modes. Multiple parameterizations are adopted and presented in this section.

5.8.1 Fermion and gauge boson couplings

The model studied in this section probes the universal coupling strength scale factors $\kappa_V = \kappa_W = \kappa_Z$ for all vector bosons and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$ for all fermions. The effective couplings corresponding to the ggH and $H \rightarrow \gamma\gamma$ vertex loops are resolved in terms of the fundamental SM couplings. It is assumed that there are no invisible or undetected Higgs boson decays, i.e. $B_{\text{inv}} = B_{\text{undet}} = 0$. $\kappa_V \geq 0$ and $\kappa_F \geq 0$ are assumed as a negative relative sign has been excluded [94]. The best-fit values and uncertainties from a combined fit are

$$\kappa_V = 1.05 \pm 0.04$$

$$\kappa_F = 1.05 \pm 0.09.$$

The scan results are shown in Fig. 5.12, the expected values are $\kappa_V = 1.00^{+0.04}_{-0.04}$ and $\kappa_F = 1.00^{+0.09}_{-0.09}$ at 68% C.L..

Figure 5.13 shows the results of the combined fit in the (κ_V, κ_F) plane as well as the contributions of the individual decay modes in this benchmark model. Both κ_V and κ_F are measured to be compatible with the SM expectation.

The compatibility of the SM hypothesis with the best fit point corresponds to a p -value of $p_{\text{SM}} = 41\%$, computed using the procedure outlined in Section 5.5 with two degrees of freedom. In the combined measurement a linear correlation of 44% between κ_V and κ_F is observed.

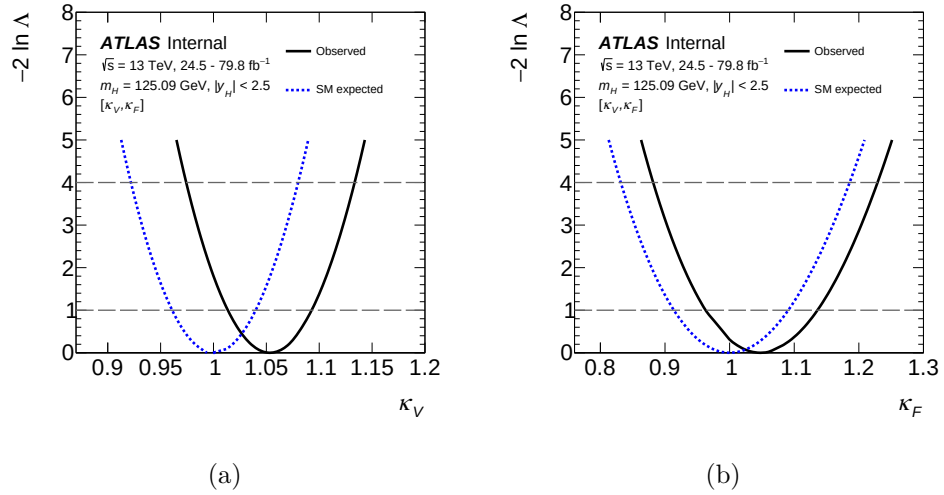


Fig. 5.12: NLL scan of (a) κ_V and (b) κ_F .

Figure 5.14 shows the same combined contours as shown in Figure 5.13, without the contours for the inputs analyses overlaid.

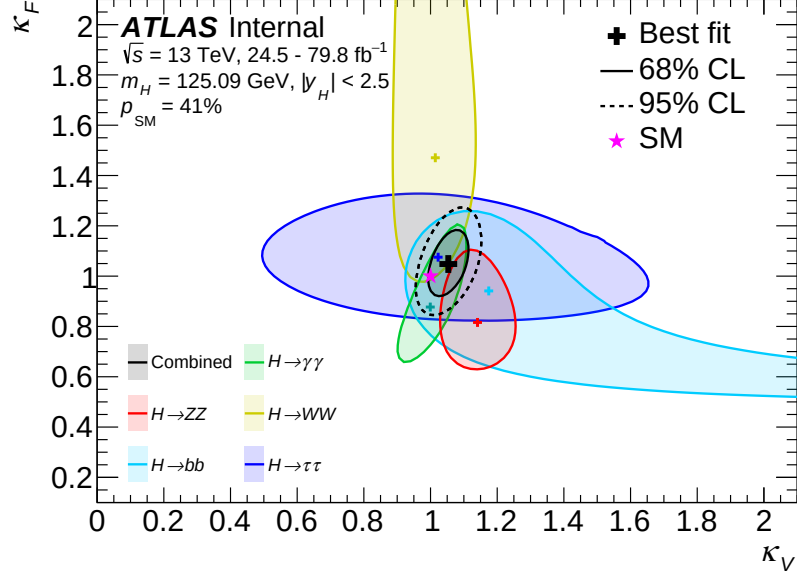


Fig. 5.13: Negative log-likelihood contours at 68% and 95% CL in the (κ_V^f, κ_F^f) plane for the individual decay modes and their combination (κ_F versus κ_V shown in black) assuming the coupling strength of fermions and vector bosons to be positive. No contributions from invisible or undetected Higgs boson decays are assumed. The long tails in the $H \rightarrow b\bar{b}(H \rightarrow WW^{(*)})$ contours towards high values of $|\kappa_V|(|\kappa_F|)$ are the result of an asymptotically disappearing sensitivity of the observed signal strength in the $b\bar{b}(WW^{(*)})$ final states to $\kappa_V(\kappa_F)$ at large values of $\kappa_V(\kappa_F)$. The best fit value for each measurement is indicated by a cross while the SM hypothesis is indicated by a star.

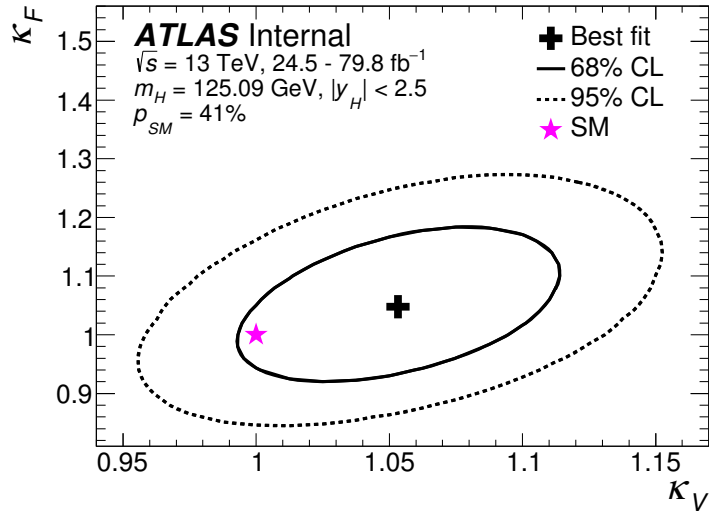


Fig. 5.14: Observed contours at 68% and 95% CL in the (κ_F, κ_V) plane, defined in the asymptotic approximation by $-2 \ln \Lambda = 2.28$ and 5.99 , respectively. The cross indicates the best-fit value and the star indicates the SM prediction.

5.8.2 Probing BSM contributions in loops and decays

The effective coupling strengths to photons and gluons in loops κ_γ and κ_g are measured. These parameters are defined to be positive as there is by construction no sensitivity to the sign of these coupling strengths. The modifiers corresponding to loop-induced processes are resolved. All the other coupling strength modifiers of known SM particles are set to the SM predictions. The potential new particles contributing to these vertex loops may or may not contribute to the total width of the Higgs boson through invisible or undetected BSM decays. In the former case, the total width is parametrized in terms of the branching fractions B_{inv} and B_{undet} defined in Section 1.4. Assuming $B_{\text{inv}} = B_{\text{undet}} = 0$, the best-fit values and uncertainties from a combined fit are

$$\begin{aligned}\kappa_\gamma &= 1.00 \pm 0.06 \\ \kappa_g &= 1.03^{+0.07}_{-0.06}.\end{aligned}$$

Figure 5.15 shows the observed and expected negative log-likelihood scans of the κ_γ and κ_g parameters under the assumption that $B_{\text{inv}} = B_{\text{undet}} = 0$.

Figure 5.16 shows log-likelihood contours obtained from the combined fit in the $(\kappa_\gamma, \kappa_g)$ plane under the assumption that $B_{\text{inv}} = B_{\text{undet}} = 0$. Both κ_γ and κ_g are measured to be compatible with the SM expectation. The compatibility of the SM hypothesis with the best fit point corresponds to a p -value of $p_{\text{SM}} = 88\%$, computed using the procedure outlined in Section 5.5 with two degrees of freedom. In the combined measurement a linear correlation of -44% between κ_γ and κ_g is observed, mainly due to the constraint on their product from the rate of $H \rightarrow \gamma\gamma$ decays in the $gg \rightarrow H$ channel.

When consider B_{inv} and B_{undet} as independent parameters in the Higgs total width, the analysis of Higgs boson decays to invisible final states (Section 5.3.8) are included in the combination and used to constrain B_{inv} . The B_{undet} parameter is constrained by decay modes that do not involve a loop process. The results from this model are

$$\begin{aligned}\kappa_\gamma &= 0.97 \pm 0.06 \\ \kappa_g &= 0.95 \pm 0.08 \\ B_{\text{inv}} &< 0.46 \text{ at } 95\% \text{ CL} \\ B_{\text{undet}} &< 0.12 \text{ at } 95\% \text{ CL}.\end{aligned}$$

The expected upper limits at 95% CL on B_{inv} and B_{undet} are 0.23 and 0.32 respectively. The compatibility of the SM hypothesis with the best fit point corresponds to a p -value of $p_{\text{SM}} = 25\%$, computed using the procedure outlined in Section 5.5 with four degrees of freedom.

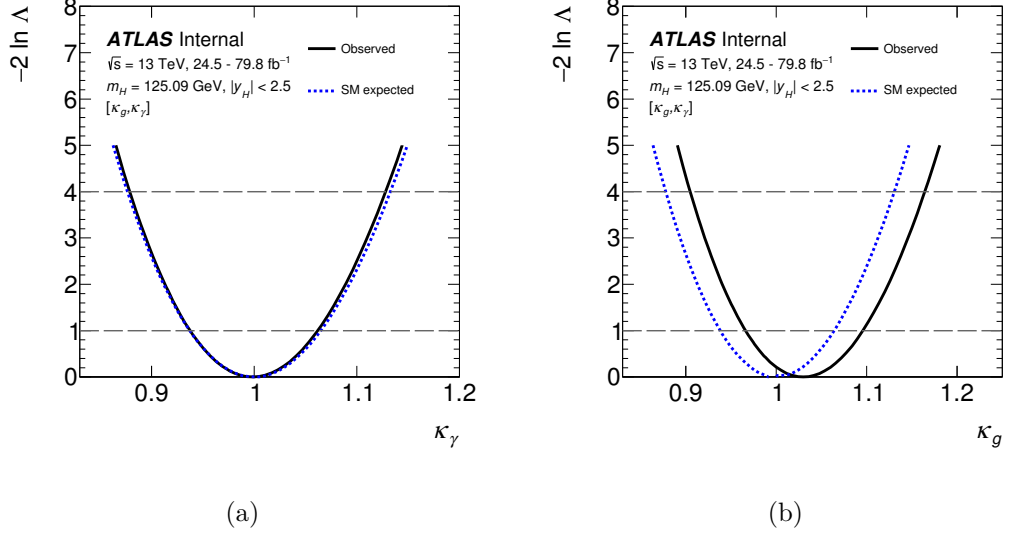


Fig. 5.15: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the (a) κ_γ and (b) κ_g parameters from a combined fit excluding searches both for off-shell Higgs production and for Higgs decays into invisible final states.

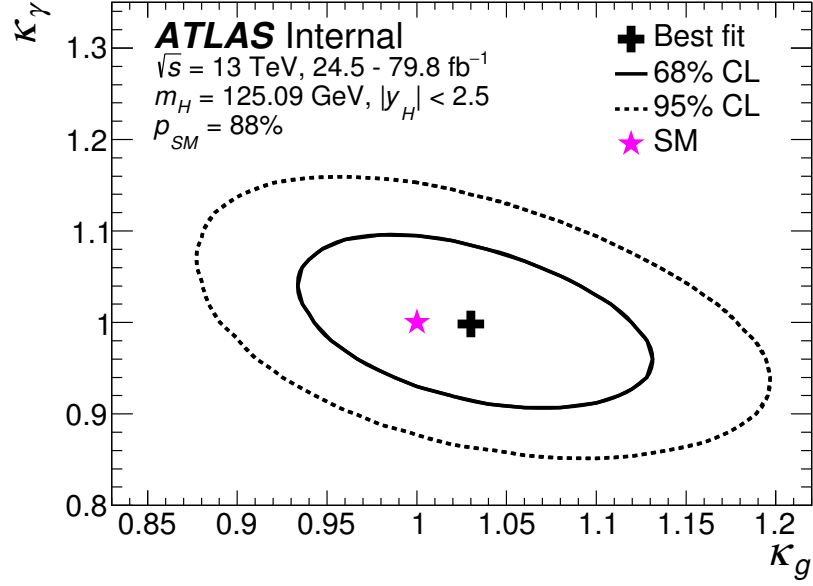


Fig. 5.16: Negative log-likelihood contours at 68% and 95% CL in the $(\kappa_\gamma, \kappa_g)$ plane obtained from a combined fit, constraining all other coupling strength modifiers to their SM values and assuming no contributions from invisible or undetected Higgs boson decays. The best fit value for each measurement is indicated by a cross while the SM hypothesis is indicated by a star.

Figure 5.17 shows the observed and expected negative log-likelihood scans of the κ_g , κ_γ , B_{inv} and B_{undet} parameters from a combined fit including searches for Higgs decays into invisible final states. Figure 5.18 shows the negative log-likelihood contours at 68% and 95% CL in the $(B_{\text{inv}}, B_{\text{undet}})$ plane obtained in this model. Figure 5.19 shows the correlation matrix obtained in fits to data using the model described in Section 5.8.2.

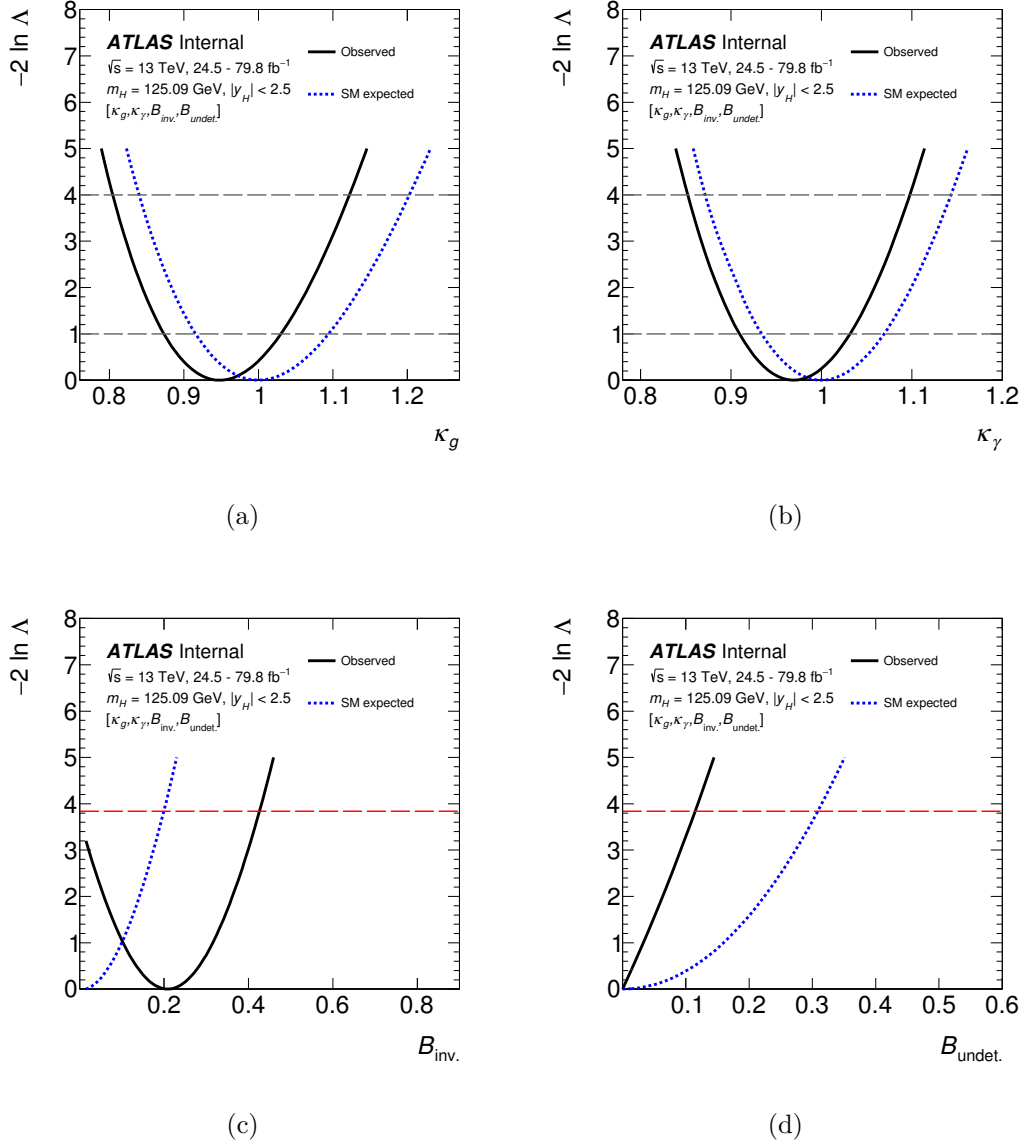


Fig. 5.17: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the (a) κ_g , (b) κ_γ , (c) B_{inv} and (d) B_{undet} parameters from a combined fit including searches for Higgs decays into invisible final states. All the other parameters of interest from the list in the legend are also varied in the minimization procedure. In (a) and (b), the dashed horizontal lines at $-2 \ln \Lambda = 1$ ($-2 \ln \Lambda = 4$) indicate the levels used to define the 1σ (2σ) confidence interval for κ_g and κ_γ . In (c) and (d), the dashed red line shows the level used to obtain the 95% CL upper limits on B_{inv} and B_{undet} .

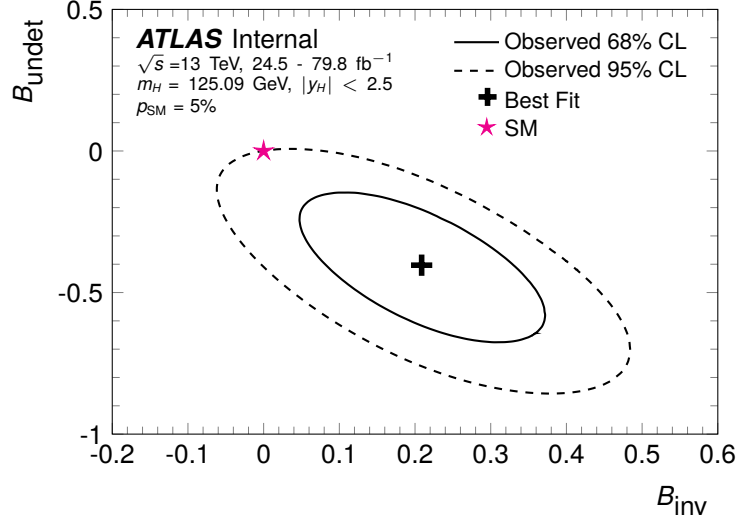


Fig. 5.18: Negative log-likelihood contours at 68% and 95% CL in the $(B_{\text{inv}}, B_{\text{undet}})$ plane obtained in the model with BSM contributions to loop and decay processes described in the text. The κ_g and κ_γ parameters are profiled, while all other coupling-strength modifiers are fixed to their SM values. The best-fit value is indicated by a cross while the SM hypothesis is indicated by a star.

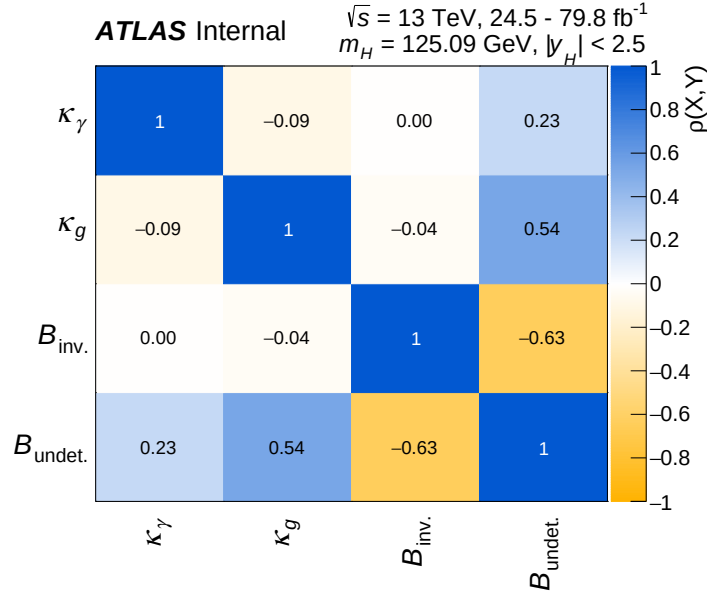


Fig. 5.19: Correlation matrix obtained in the fit to the data of a model that probes BSM contributions in loops and decays, with B_{BSM} included as a free parameter.

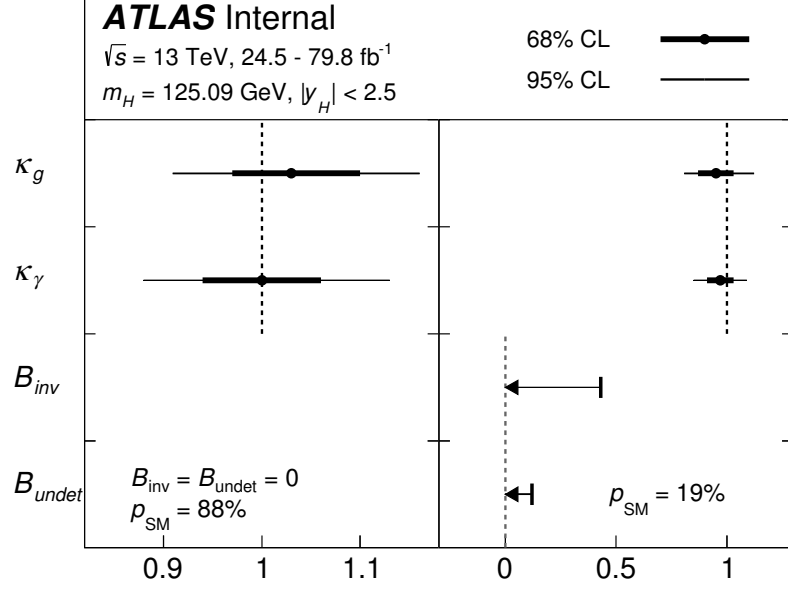


Fig. 5.20: Best-fit values and uncertainties for effective modifiers to the photon and gluon couplings of the Higgs boson, with either $B_{inv} = B_{undet} = 0$ (left), or B_{inv} and B_{undet} included as free parameters (right). In the latter case, the measurements of the Higgs boson decay rate to invisible final states are included in the combination. The SM corresponds to $\kappa_\gamma = \kappa_g = 1$ and $B_{inv} = B_{undet} = 0$. All coupling strength modifiers of known SM particles are assumed to be unity, i.e. they follow the SM predictions.

The results for the two models are summarized in Fig. 5.20.

5.8.3 Generic parametrization assuming no new particles in loops and decays

It is allowed to study in detail the Higgs coupling with each particle with multiple channels combined. In this generic model the coupling scale factors for the coupling strengths to W , Z , t , b , τ and μ are treated independently. The coupling strength to c quark is assumed to scale as the couplings to the t quark. SM values are assumed for the other fermions. Invisible or undetected BSM Higgs boson decays are assumed not to exist. All coupling strength scale factors are assumed to be positive. The results of the $H \rightarrow \mu\mu$ analysis are included for this specific benchmark model. The results are shown in Table 5.14.

Good agreements with the SM prediction are found for all measured coupling-strength scale factors in this generic model. The compatibility of the SM prediction corresponds to a p -value of $p_{SM} = 76\%$, computed using the procedure outlined in Section 5.5 with six degrees of freedom. Figure 5.21 shows the coupling strength scale factors as a function of particle masses.

$$y_{V,i} = \sqrt{\kappa_{V,i} \frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i} \frac{m_{V,i}}{v}} \quad (5.19)$$

for weak bosons with a mass m_V , where $g_{V,i}$ is the absolute Higgs boson coupling strength and $v = 246 \text{ GeV}$ is the vacuum expectation value of the Higgs field, and

$$y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{v} \quad (5.20)$$

for fermions as a function of the particle mass m_F , assuming a SM Higgs boson with a mass of 125.09 GeV . For the b -quark mass the $\overline{MS}$ running mass evaluated at a scale of 125.09 GeV is assumed.

mass(GeV)		Observed	expected
κ_Z	91.2	$1.10^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$
κ_W	80.4	$1.05^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$
κ_b	2.76	$1.06^{+0.19}_{-0.18}$	$1.00^{+0.20}_{-0.19}$
κ_t	169.2	$1.02^{+0.11}_{-0.10}$	$1.00^{+0.12}_{-0.11}$
κ_τ	1.777	$1.07^{+0.15}_{-0.15}$	$1.00^{+0.16}_{-0.15}$
κ_μ	0.113	< 1.53	< 1.81

Table. 5.14: Masses and fit results for κ_Z , κ_W , κ_b , κ_t , κ_τ and κ_μ . Both the observed and expected results are shown. The upper limit on κ_μ is set using the CL_s prescription.

Figure 5.22 shows the correlation matrix obtained in fits to data using the model described in Section 5.8.3.

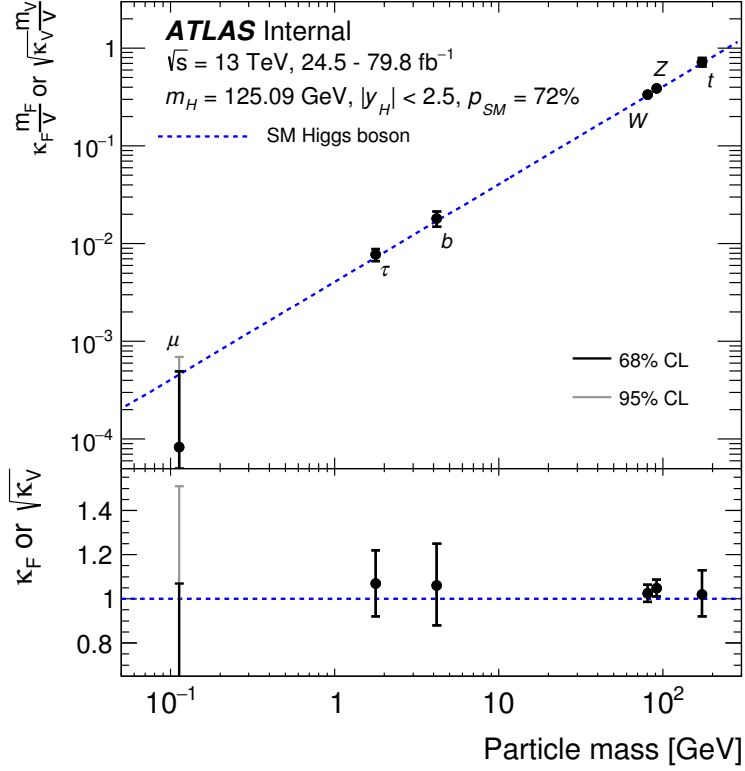


Fig. 5.21: Reduced coupling strength modifiers $\kappa_F \frac{m_F}{v}$ for fermions ($F = t, b, \tau, \mu$) and $\sqrt{\kappa_V} \frac{m_V}{v}$ for weak gauge bosons ($V = W, Z$) as a function of their masses m_F and m_V , respectively, and the vacuum expectation value of the Higgs field $v = 246 \text{ GeV}$. The SM prediction for both cases is also shown (dotted line). The black error bars represent 68% CL intervals on the measured parameters. For κ_μ the light error bars indicate the 95% CL interval. The couplings modifiers κ_F and κ_V are measured assuming no BSM contributions to the Higgs boson decays, and the SM structure of loop processes such as $gg \rightarrow H$, $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$. The lower inset shows the ratios of the values to their SM predictions.

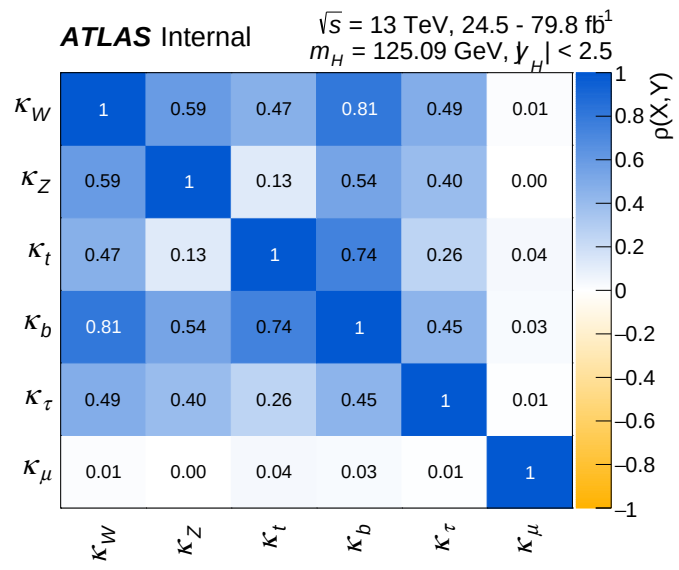


Fig. 5.22: Correlation matrix of the generic parameterization assuming no new particles in loops and decays.

5.8.4 Generic parameterization including effective photon and gluon couplings with and without BSM contributions in decays

This section presents the parameterization very similar to the one in Section 5.8.3, but without resolving the $gg \rightarrow H$, $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ loop processes. The effective coupling strength modifiers κ_g and κ_γ are included.

For parameters including κ_Z , κ_W , κ_b , κ_t , κ_τ , κ_γ and κ_g , only the sign of κ_t can go either positive or negative. The others are assumed to be positive. Three interpretations of the Higgs total width are performed based on different channels combined:

- (a) No BSM contributions to the total width ($B_{\text{inv}} = B_{\text{undet}} = 0$).
- (b) Both B_{inv} and B_{undet} are added as free parameters to the model. The $H \rightarrow$ invisible channel (Section 5.3.8) are included in the combination to provide a constraint on B_{inv} . B_{inv} is allowed to go both positive and negative. To constrain the total width, the assumptions $\kappa_W \leq 1$ and $\kappa_Z \leq 1$ are introduced.
- (c) A single free parameter $B_{\text{BSM}} = B_{\text{inv}} + B_{\text{undet}}$ is added to the model. The $H \rightarrow$ offshell (Section 5.3.9) is included in the combination to provide a constraint on B_{BSM} and B_{BSM} is assumed to be positive.

The results of three parameterizations are summarized in Table 5.15 and Figure 5.28. All probed fundamental coupling-strength scale factors, as well as the probed loop-induced coupling scale factors are measured to be compatible with their SM expectation under all explored assumptions. Upper limits are set on the fraction of Higgs boson decays to invisible or undetected BSM decays. In scenario (b) the observed (expected) 95% CL upper limits on the branching ratios are $B_{\text{inv}} < 0.30$ (0.18) and $B_{\text{undet}} < 0.22$ (0.38), and the lower limits on the couplings to vector bosons are $\kappa_Z > 0.87$ (0.76) and $\kappa_W > 0.86$ (0.77). In scenario (c), the observed (expected) upper limit on B_{BSM} is 0.47 (0.57). The compatibility of the SM hypothesis with the best-fit point in scenario (a) is $p_{\text{SM}} = 88\%$, computed using the procedure outlined in Section 5.5 with seven degrees of freedom and B_{BSM} fixed to zero. For scenarios (b), due to the boundary set for $\kappa_{W,Z} \leq 1$ and $B_{\text{undet}} > 0$ breaking the asymptotic assumption, the compatibility cannot be derived by using method described in section 5.5. A toy-based method is used to calculate the compatibility. With comparing to the test statistic of the observed result to 500 toys, the compatibility $p_{\text{SM}} = 96\%$. For scenario (c) the values $p_{\text{SM}} = 95\%$, are obtained, respectively, using eight degrees of freedom in the computation.

Figure 5.23 shows the observed and expected negative log-likelihood scans of the κ_W , κ_Z , κ_t , κ_b , κ_τ , κ_γ and κ_g parameters from a combined fit using a generic

Parameter	(a) $B_{\text{inv}} = B_{\text{undet}} = 0$	(b) B_{inv} free, $B_{\text{undet}} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{\text{BSM}} \geq 0$, $\kappa_{\text{off}} = \kappa_{\text{on}}$
κ_Z	1.11 ± 0.08	> 0.87 at 95% CL	$1.16^{+0.18}_{-0.13}$
κ_W	1.05 ± 0.09	> 0.85 at 95% CL	$1.12^{+0.18}_{-0.15}$
κ_b	$1.03^{+0.19}_{-0.17}$	0.88 ± 0.13	$1.08^{+0.25}_{-0.20}$
κ_t	$1.09^{+0.15}_{-0.14}$	$[-1.03, -0.79] \cup [0.93, 1.24]$ at 68% CL	$1.14^{+0.19}_{-0.18}$
κ_τ	$1.05^{+0.16}_{-0.15}$	0.97 ± 0.13	$1.12^{+0.23}_{-0.21}$
κ_γ	1.05 ± 0.09	0.98 ± 0.07	$1.10^{+0.19}_{-0.13}$
κ_g	$0.99^{+0.11}_{-0.10}$	$1.01^{+0.13}_{-0.11}$	$1.02^{+0.22}_{-0.13}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.22 at 95% CL	-
B_{BSM}	-	-	< 0.47 at 95% CL

Table. 5.15: Fit results for Higgs boson coupling modifiers per particle type with effective photon and gluon couplings and either (a) $B_{\text{inv}} = B_{\text{undet}} = 0$, (b) B_{inv} and B_{undet} included as free parameters, the conditions $\kappa_{W,Z} \leq 1$ applied and the measurement of the Higgs boson decay rate to invisible final states included in the combination, or (c) $B_{\text{BSM}} = B_{\text{inv}} + B_{\text{undet}}$ included as a free parameter, the measurement of off-shell Higgs boson production included in the combination, and the assumptions described in the text applied on the off-shell coupling-strength scale factors.

coupling parameterization without BSM contributions to the decays, described in Section 5.8.4. Figure 5.24 and 5.25 show the observed and expected negative log-likelihood scans of the B_{inv} and B_{undet} parameters from a combined fit including searches for Higgs decays into invisible final states using a generic coupling parameterization. Figure 5.26 shows the observed and expected negative log-likelihood scans of the B_{BSM} parameter from a combined fit including searches for off-shell Higgs production using a generic coupling parameterization. Figure 5.27 shows the correlation matrix obtained in fits to data using the models described in Section 5.8.4.

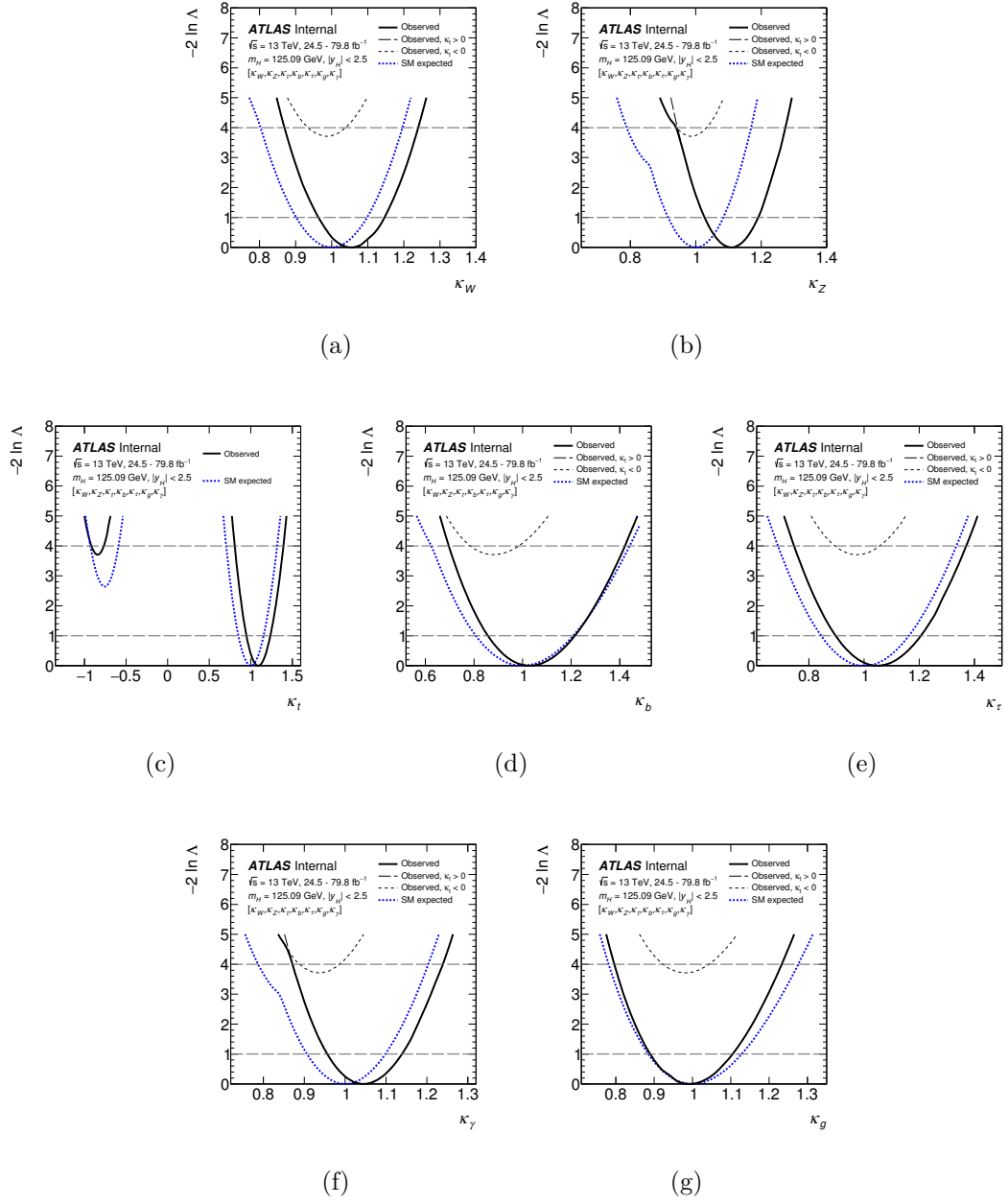


Fig. 5.23: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the (a) κ_W , (b) κ_Z , (c) κ_t , (d) κ_b , (e) κ_τ , (f) κ_γ and (g) κ_g parameters from a combined fit using a generic coupling parameterization without BSM contributions to the decays. All the other parameters of interest from the list in the legend are also varied in the minimization procedure. The dashed horizontal lines at $-2 \ln \Lambda = 1$ ($-2 \ln \Lambda = 4$) indicate the levels used to define the 1σ (2σ) confidence interval for the corresponding parameter.

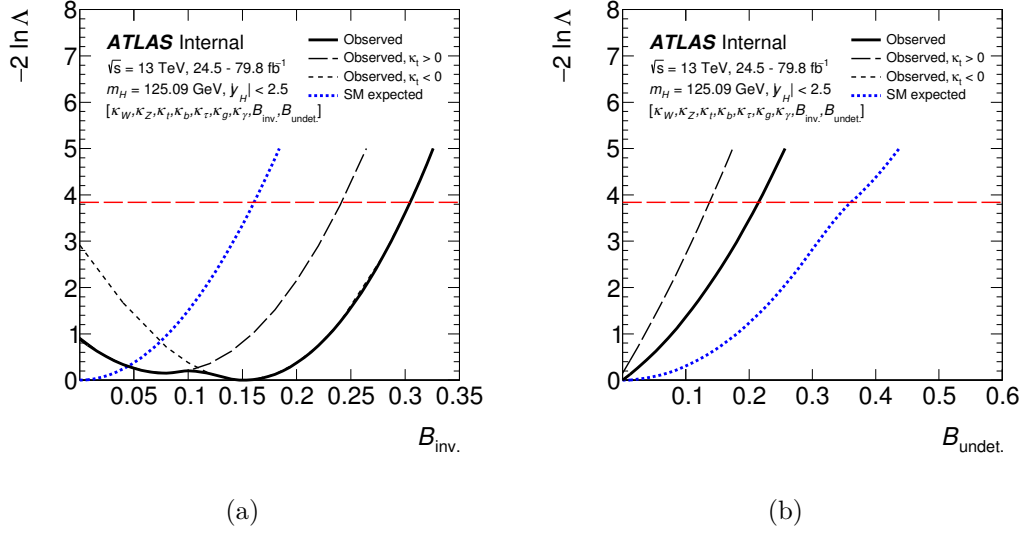


Fig. 5.24: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the (a) B_{inv} , (b) B_{undet} parameters from a combined fit including searches for Higgs decays into invisible final states using a generic coupling parameterization. All the other parameters of interest from the list in the legend are also varied in the minimization procedure. The dashed red horizontal lines indicate the levels used to obtain the 95% CL upper limits on B_{inv} and B_{undet} .

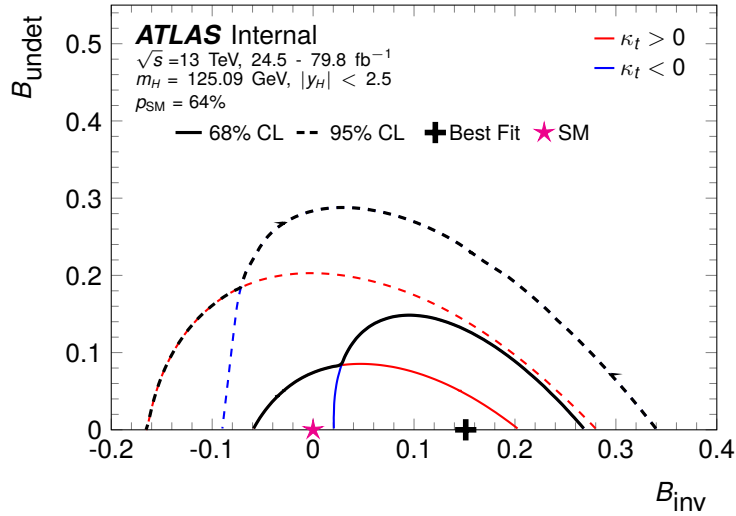


Fig. 5.25: Negative log-likelihood contours at 68% and 95% CL in the $(B_{\text{inv}}, B_{\text{undet}})$ plane obtained in the model with B_{inv} and B_{undet} included as free parameters, the conditions $\kappa_{W,Z} \leq 1$ applied and the measurement of the Higgs boson decay rate into invisible final states included in the combination. The coupling-strength modifiers are profiled. The best-fit value is indicated by a cross while the SM hypothesis is indicated by a star.

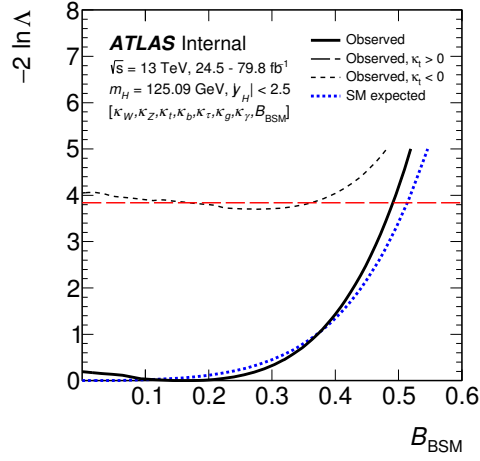


Fig. 5.26: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the B_{BSM} parameter from a combined fit including searches for off-shell Higgs production using a generic coupling parameterization. All the other parameters of interest from the list in the legend are also varied in the minimization procedure. The dashed red horizontal line indicates the level used to obtain the 95% CL upper limit on B_{BSM} .

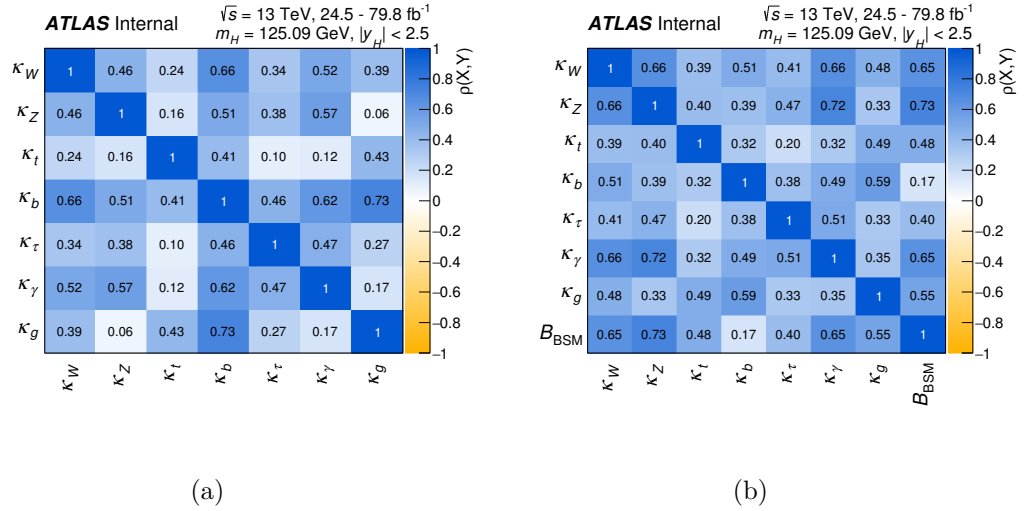


Fig. 5.27: Correlation matrix obtained in the fit to the data using generic parameterizations with effective photon and gluon couplings with (a) $B_{\text{inv}} = B_{\text{undet}} = 0$ or (b) B_{inv} and B_{undet} included as free parameters. The latter is constrained using the off-shell analysis.

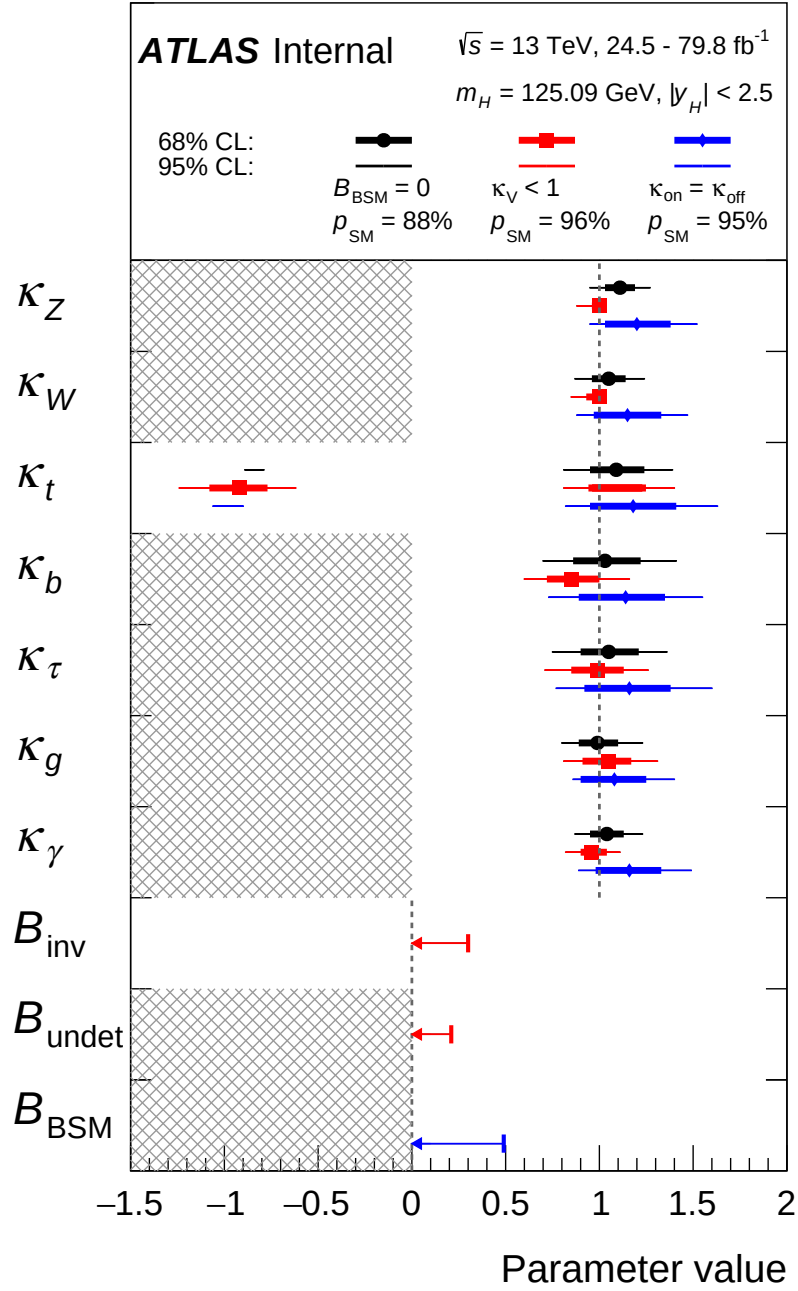


Fig. 5.28: Best-fit values and uncertainties for Higgs boson coupling modifiers per particle type with effective photon and gluon couplings and either $B_{\text{inv}} = B_{\text{undet}} = 0$ (black); B_{inv} and B_{undet} included as free parameters, the conditions $\kappa_{W,Z} \leq 1$ applied and the measurement of the Higgs boson decay rate to invisible final states included in the combination (red); or $B_{\text{BSM}} = B_{\text{inv}} + B_{\text{undet}}$ included as a free parameter, the measurement of off-shell Higgs boson production included in the combination, and the assumptions described in the text applied on the off-shell coupling-strength scale factors (blue). The SM corresponds to $B_{\text{inv}} = B_{\text{undet}} = 0$ and all κ parameters set to unity. All parameters except κ_t are assumed to be positive.

5.8.5 Generic parameterization using ratios of coupling modifiers

By using ratios of coupling modifiers, the assumption on the Higgs total width can be removed. Table 5.16 shows the parameters of interest in this parameterizations. All parameters are assumed to be positive. The numerical results from the fit to this benchmark model are summarized in Table 5.16 and visualized in Figure 5.31. All model parameters are measured to be compatible with their SM expectation. The compatibility of the SM hypothesis with the best fit point corresponds to a p -value of $p_{\text{SM}} = 85\%$, computed using the procedure outlined in Section 5.5 with seven degrees of freedom.

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.06 ± 0.07
λ_{tg}	κ_t / κ_g	$1.10^{+0.15}_{-0.14}$
λ_{Zg}	κ_Z / κ_g	$1.12^{+0.15}_{-0.13}$
λ_{WZ}	κ_W / κ_Z	0.95 ± 0.08
$\lambda_{\gamma Z}$	κ_γ / κ_Z	0.94 ± 0.07
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.95 ± 0.13
λ_{bZ}	κ_b / κ_Z	$0.93^{+0.15}_{-0.13}$

Table. 5.16: Best-fit values and uncertainties for ratios of coupling modifiers. The second column provides the expression of the measured parameters in terms of the coupling modifiers defined in previous sections. All parameters are defined to be unity in the SM.

Figure 5.29 shows the observed and expected negative log-likelihood scans of the $\lambda_{\gamma Z}$, λ_{tg} , λ_{bZ} and λ_{WZ} parameters from a combined fit using a generic coupling parameterization without assumptions about the Higgs boson total width, described in Section 5.8.5. Figure 5.30 shows the correlation matrix obtained in fits to data.

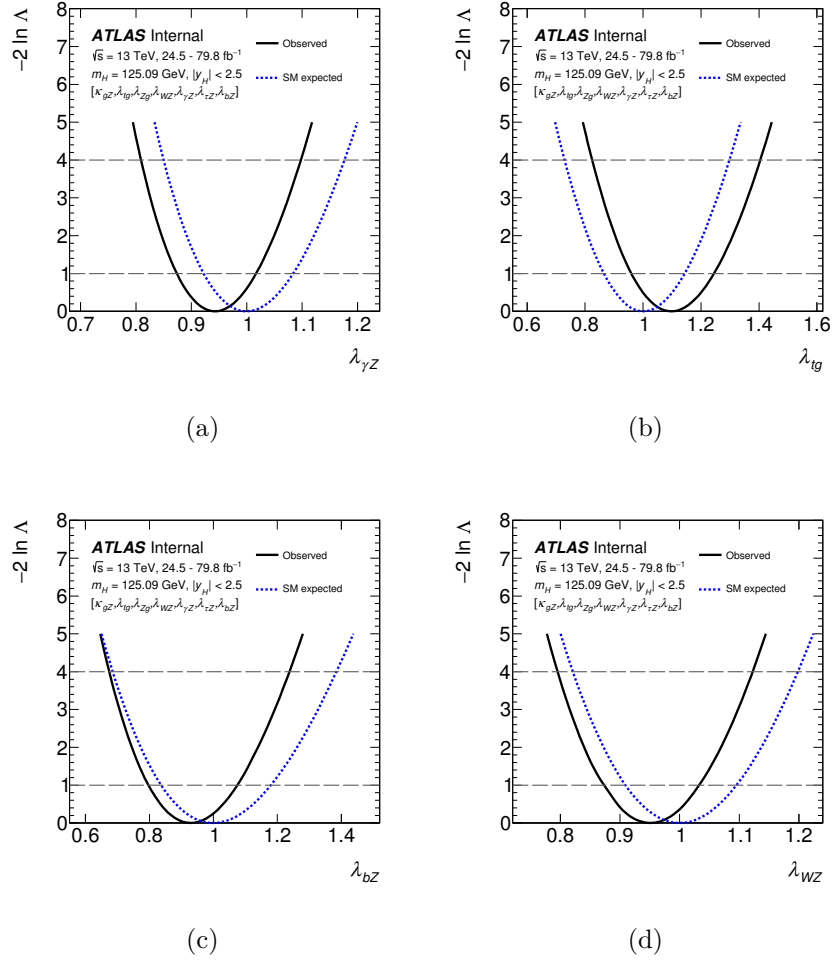


Fig. 5.29: Observed (solid line) and expected (dotted line) negative log-likelihood scan of the (a) $\lambda_{\gamma Z}$, (b) λ_{tg} , (c) λ_{bZ} , and (d) λ_{WZ} parameters from a combined fit using a generic coupling parameterization without assumptions about the Higgs boson total width. All the other parameters of interest from the list in the legend are also varied in the minimization procedure. The dashed horizontal lines at $-2 \ln \Lambda = 1$ ($-2 \ln \Lambda = 4$) indicate the levels used to define the 1σ (2σ) confidence interval for the corresponding parameter.

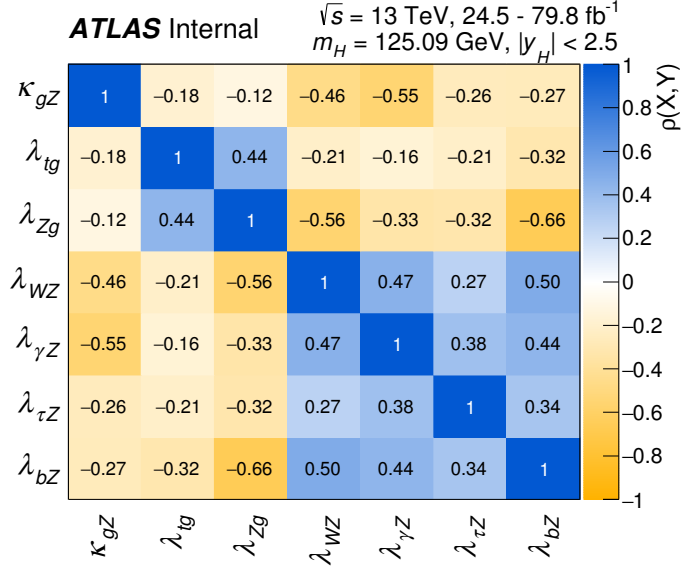


Fig. 5.30: Correlation matrix obtained in the fit to the data using a generic parameterization using ratios of coupling modifiers.

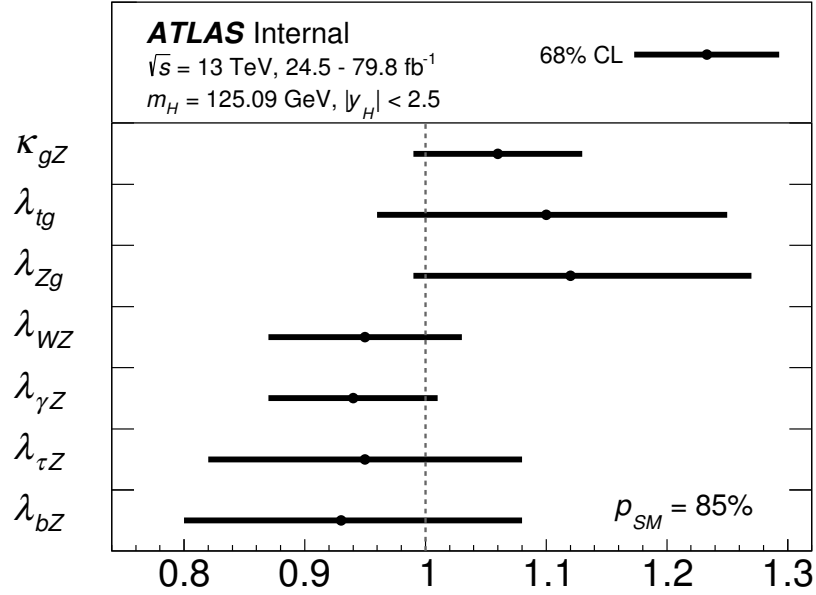


Fig. 5.31: Measured ratios of coupling modifiers. The dashed line indicates the SM value of unity for each parameter.

5.9 Summary

Combined measurements are presented based on Higgs boson production cross sections and branching ratios using up to 79.8 fb^{-1} of proton–proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and recorded by the ATLAS detector.

The analysis is based on the measurements performed in the individual $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$ and $H \rightarrow \mu\mu$ decay modes, searches for decays into invisible final states, as well as on measurements of off-shell Higgs boson production.

The global signal strength is determined to be $\mu = 1.11^{+0.09}_{-0.08}$.

The Higgs boson production cross sections are measured in $|y_H| < 2.5$ for the gluon fusion process, vector-boson fusion, the associated production with a W or Z boson and the associated production with top quarks, assuming the SM Higgs branching ratios to different Higgs decay modes. The combined measurement leads to an observed (expected) significance for the vector-boson fusion production process of 6.5σ (5.3σ). For the VH production mode the observed (expected) significance is 5.3σ (4.7σ). The $t\bar{t}H + tH$ processes are measured with an observed (expected) significance of 5.8σ (5.3σ).

Ratios of these cross sections and of the branching ratios are also measured by using the reference process $gg \rightarrow H \rightarrow ZZ^*$. Another measurement is performed for the production cross section times branching fraction for each pair of production and decay processes to which the combined analyses are sensitive. No significant deviation from the Standard Model predictions is observed.

The observed Higgs boson cross sections are also measured by using the Stage 1 Simplified Template Cross-section framework. The measurements in all regions are found to be compatible with SM predictions.

The observed Higgs boson yields are used to obtain confidence intervals for κ modifiers to the couplings of the SM Higgs boson to fermions, weak vector bosons, gluons, and photons and to the branching ratio of the Higgs boson to invisible and undetected decay modes. A variety of physics-motivated constraints on the Higgs boson total width are explored: Using searches for $H \rightarrow$ invisible and constraints on couplings to vector bosons, the branching fraction of invisible Higgs boson decays into BSM particles is constrained to be less than 30% at 95% CL, while the branching fraction of decays into undetected particles is less than 22% at 95% CL. The overall branching fraction of the Higgs boson into BSM decays is determined to be less than 47% at 95% CL using measurements of off-shell Higgs boson production in combination with measurements of SM Higgs boson production and rates. No significant deviation from the Standard Model predictions is observed in any of the benchmark models studied.

Conclusion

By using 36.1 fb^{-1} of proton–proton collision data produced by the LHC at $\sqrt{s} = 13 \text{ TeV}$ and collected by the ATLAS detector, measurements of Higgs boson production cross sections and couplings in the diphoton decay channel have been performed. All measurements assume a Higgs boson mass of $125.09 \pm 0.24 \text{ GeV}$. Simplified template cross sections and total production mode cross sections offer the possibility to separate the different Higgs boson production processes. They are measured for gluon fusion, vector boson fusion production and production in association with a vector boson or top quarks. Several parameters in the κ model which explore the Higgs coupling structure are measured as well. The inclusive signal strength is measured $\mu = 0.99_{-0.14}^{+0.14}$, with an improvement on precision at a level of 40% comparing to the ATLAS Run 1 result. No significant deviation from the Standard Model expectations is observed.

A precise measurement of the combined Higgs properties is performed in ATLAS experiment based on the up to 80 fb^{-1} of data collected at a proton–proton collision energy of 13 TeV from 2015 to 2017. All of the main decay channels of the Higgs boson are taken into account including pairs of photons, W and Z bosons, bottom quarks, taus, and muons. It is observed that the overall production rate of the Higgs boson is in an agreement with the Standard Model prediction with an uncertainty of 8%. A significance of more than 5 standard deviations is reached on the ATLAS experiment for all four major production modes: the dominated gluon-gluon fusion mode, the associated production with top-quark pair, the production in association with a weak boson, and the first single-experiment observation of the VBF production mode, corresponding to an observed (expected) significance 6.5σ (5.3σ). The Higgs coupling to the other particles are confirmed, at precision levels of less than 10% for W and Z , 10% for t , and 20% for b and τ , respectively. These results are with improvements on precision from 20% to 30% comparing to the ATLAS + CMS Run 1 results. All results are compatible with the SM predictions, painting a complete picture of Higgs boson.

The consistency between the results and the Standard Model Higgs boson prediction motivates higher precision measurements. There is a significant boost

in production cross sections when increasing the center-of-mass energy of LHC from 8 TeV to 13 and 14 TeV. This along with a relatively larger integrated luminosity delivered, allows a more precise measurement to probe the Higgs sector more deeply.

By the end of year LHC Run 3, the data collected by the ATLAS detector is expected to correspond to 300 fb^{-1} . The precision on the measured parameters will benefit from the larger integrated luminosity.

The possible future facilities are also expected to deliver better results of the Higgs sector in the Standard Model, including HL-LHC [138] which have advantages in measuring decay modes with a low rate and rare processes, and CEPC [139] which can more precisely determine the absolute Higgs boson couplings.

The physics prospects of the ATLAS experiment at the HL-LHC with 3000 fb^{-1} integrated luminosity data collected at $\sqrt{s} = 14 \text{ TeV}$, for measuring the Higgs boson production and decay rates and coupling strengths are studied [140]. The large dataset will allow both to significantly improve the precision on the measured Higgs properties, and to observe the currently unobserved decay modes $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$.

After taking the expected improvements on the theoretical calculations and the better understanding of the detector in to account, a prevision at the level of few percents will be reached on all the production-mode cross sections and on the main decay channels. Only the measurement precision for the $W(Z)H$, $H \rightarrow \gamma\gamma$, VH , $H \rightarrow ZZ^{(*)}$ and $t\bar{t}H$, $H \rightarrow ZZ^{(*)}$ channels, and the two currently unobserved decay modes will be limited by statistical uncertainty. The expected result from HL-LHC for the measurement of each Higgs boson coupling modifier per particle type is shown in Figure 5.32

The possible Higgs physics programs at the CEPC are also studied [141]. An unprecedented precision at a percent level or better will be reached for most of Higgs boson couplings, in particular a 0.25% precision can be determined of the coupling to the Z boson. Furthermore, thanks to the characteristic of lepton colliders, the clean event environment of the CEPC will allow the identification of potential unknown decay modes, which are very challenging at the hadron colliders. The expected uncertainties from CEPC and the combined CEPC+HL-LHC for the measurement of each Higgs boson coupling modifier per particle type is shown in Figure 5.33

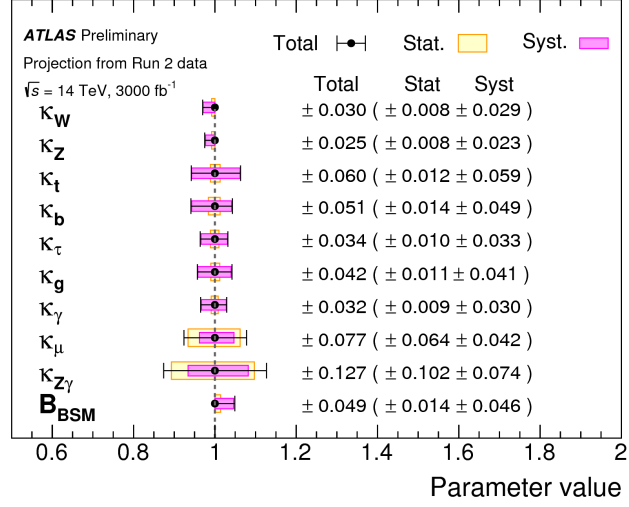


Fig. 5.32: Expected result for the measurement of each Higgs boson coupling modifier per particle type. All parameters except κ_t are assumed to be positive. The conditions $\kappa_{W,Z} \leq 1$ are applied. The SM corresponds to $B_{BSM} = 0$ and all κ parameters equal to unity. Source: ATL-PHYS-PUB-2018-054.

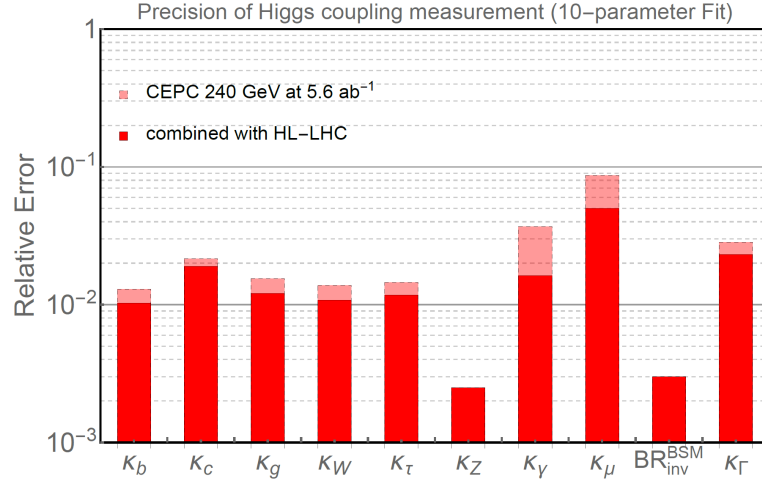


Fig. 5.33: 10 parameter fit results for the CEPC at 240 GeV with an integrated luminosity of 5.6 ab^{-1} (light red bars) and for the combination with the HL-LHC inputs (dark red bars). All the numbers are relative precision except for BR_{inv}^{BSM} for which the 95% CL upper limit are quoted. Source: CEPC Conceptual Design Report: Volume 2.

REFERENCES

- [1] ATLAS Collaboration. Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector. *Phys. Rev. D*, 90:112015, 2014.
- [2] LHC Higgs Cross Section Working Group, S. Heinemeyer et al. Handbook of LHC Higgs Cross Sections: 3. Higgs Properties. CERN-2013-004, 2013.
- [3] LHC Higgs Cross Section Working Group, D. de Florian et al. Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector. 2016.
- [4] ATLAS Collaboration. Measurement of the Higgs boson mass in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels with $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector. *Phys. Lett. B*, 784:345, 2018.
- [5] Peter W. Higgs. Broken Symmetries and the Masses of Gauge Bosons. *Phys. Rev. Lett.*, 13:508, 1964.
- [6] F. Englert and R. Brout. Broken Symmetry and the Mass of Gauge Vector Mesons. *Phys. Rev. Lett.*, 13:321, 1964.
- [7] J. R. Andersen et al. Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report. 2016.
- [8] Nikolas Kauer and Giampiero Passarino. Inadequacy of zero-width approximation for a light Higgs boson signal. *JHEP*, 1208:116, 2012.
- [9] Fabrizio Caola and Kirill Melnikov. Constraining the Higgs boson width with ZZ production at the LHC. *Phys. Rev.*, D88:054024, 2013.
- [10] ATLAS Collaboration. Constraints on the off-shell Higgs boson signal strength in the high-mass ZZ and WW final states with the ATLAS detector. *Eur. Phys. J. C*, 75:335, 2015.
- [11] ATLAS Collaboration. Constraints on off-shell Higgs boson production and the Higgs boson total width in $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states with the ATLAS detector. *Phys. Lett. B*, 786:223, 2018.
- [12] Christoph Englert, Matthew McCullough, and Michael Spannowsky. Gluon-initiated associated production boosts Higgs physics. *Phys. Rev.*, D89:013013, 2014.
- [13] P. Lebrun S. Myers R. Ostojic et al. O. S. Bruning, P. Collier. LHC Design

- Report. 1. The LHC Main Ring.
- [14] P. Lebrun S. Myers R. Ostojic et al. O. S. Bruning, P. Collier. LHC Design Report. 2. The LHC infrastructure and general services.
 - [15] V. Mertens J. Poole M. Benedikt, P. Collier and K. Schindl. LHC Design Report. 3. The LHC injector chain.
 - [16] Lyndon Evans and Philip Bryant. LHC machine. *Journal of Instrumentation*, 3(08):S08001–S08001, aug 2008.
 - [17] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.
 - [18] S. Chatrchyan et al. The CMS Experiment at the CERN LHC. *JINST*, 3:S08004, 2008.
 - [19] ALICE Collaboration et al. The ALICE experiment at the CERN LHC. *Journal of Instrumentation*, 3(08):S08002–S08002, aug 2008.
 - [20] LHCb Collaboration and Others. The LHCb detector at the LHC. *Journal of Instrumentation*, 3(08):S08005–S08005, aug 2008.
 - [21] ATLAS Collaboration. ATLAS Insertable B-layer Technical Design Report. CERN-LHCC-2010-013, ATLAS-TDR-19, 2010.
 - [22] ATLAS Collaboration. Performance of the ATLAS trigger system in 2015. *Eur. Phys. J. C*, 77:317, 2017.
 - [23] ATLAS Collaboration. The ATLAS Simulation Infrastructure. *Eur. Phys. J. C*, 70:823, 2010.
 - [24] G. Duckeck, D. Barberis, R. Hawkings, R. Jones, N. McCubbin, G. Poulard, D. Quarrie, T. Wenaus, and E. Obreshkov. ATLAS computing: Technical design report. 2005.
 - [25] S. Agostinelli et al. (GEANT4 Collaboration). GEANT4: a simulation toolkit. *Nucl. Instrum. Methods*, 506:250–303, 2003.
 - [26] J. Allison et al. (GEANT4 Collaboration). GEANT4 Developments and Applications. *IEEE Trans. Nucl. Sci.*, 53:270–278, 2006.
 - [27] ATLAS Collaboration. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data. *Eur. Phys. J. C*, 76:666, 2016.
 - [28] ATLAS Collaboration. Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data. *Eur. Phys. J.*, C74:3071, 2014.
 - [29] ATLAS Collaboration. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016. *Eur. Phys. J.*, 2018.
 - [30] ATLAS Collaboration. Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1. *Eur. Phys. J. C*, 77:490, 2017.
 - [31] ATLAS Collaboration. Electron reconstruction and identification in the

- ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} = 13$ TeV. Eur. Phys. J., 2019.
- [32] ATLAS Collaboration. Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV. Eur. Phys. J. C, 76:292, 2016.
 - [33] ATLAS Collaboration. Reconstruction of hadronic decay products of tau leptons with the ATLAS experiment. Eur. Phys. J. C, 76:295, 2016.
 - [34] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. The Anti-k(t) jet clustering algorithm. JHEP, 04:063, 2008.
 - [35] ATLAS Collaboration. Jet Calibration and Systematic Uncertainties for Jets Reconstructed in the ATLAS Detector at $\sqrt{s} = 13$ TeV. ATLAS-PHYS-PUB-2015-015, 2015.
 - [36] ATLAS Collaboration. Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV. Eur. Phys. J. C, 78:903, 2018.
 - [37] ATLAS Collaboration. Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2. Eur. Phys. J. C, 77:673, 2017.
 - [38] ATLAS Collaboration. Vertex Reconstruction Performance of the ATLAS Detector at $\sqrt{s} = 13$ TeV. ATL-PHYS-PUB-2015-026, 2015.
 - [39] ATLAS and CMS Collaborations. Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments. Phys. Rev. Lett., 114:191803, 2015.
 - [40] A. Bredenstein, Ansgar Denner, S. Dittmaier, and M.M. Weber. Radiative corrections to the semileptonic and hadronic Higgs-boson decays $H \rightarrow WW/ZZ \rightarrow 4$ fermions. JHEP, 0702:080, 2007.
 - [41] A. Bredenstein, Ansgar Denner, S. Dittmaier, and M.M. Weber. Precise predictions for the Higgs-boson decay $H \rightarrow WW/ZZ \rightarrow 4$ leptons. Phys. Rev. D, 74:013004, 2006.
 - [42] A. Bredenstein, Ansgar Denner, S. Dittmaier, and M. M. Weber. Precision calculations for the Higgs decays $H \rightarrow ZZ/WW \rightarrow 4$ leptons. Nucl. Phys. Proc. Suppl., 160:131–135, 2006.
 - [43] A. Djouadi, J. Kalinowski, and M. Spira. HDECAY: A Program for Higgs boson decays in the Standard Model and its supersymmetric extension. Comput. Phys. Commun., 108:56, 1998.
 - [44] A. Djouadi, M. M. Mühlleitner, and M. Spira. Decays of supersymmetric particles: The Program SUSY-HIT (SUSpect-SdecaY-Hdecay-InTerface). Acta Phys. Polon., B38:635–644, 2007.
 - [45] Keith Hamilton, Paolo Nason, Emanuele Re, and Giulia Zanderighi.

- NNLOPS simulation of Higgs boson production. JHEP, 1310:222, 2013.
- [46] Torbjorn Sjöstrand, Stephen Mrenna, and Peter Z. Skands. A Brief Introduction to PYTHIA 8.1. Comput. Phys. Commun., 178:852, 2008.
 - [47] ATLAS Collaboration. Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. JHEP, 09:145, 2014.
 - [48] U. Aglietti, R. Bonciani, G. Degrossi, and A. Vicini. Two loop light fermion contribution to Higgs production and decays. Phys. Lett., B595:432, 2004.
 - [49] Stefano Actis, Giampiero Passarino, Christian Sturm, and Sandro Uccirati. NLO electroweak corrections to Higgs boson production at hadron colliders. Phys. Lett. B, 670:12, 2008.
 - [50] Charalampos Anastasiou, Claude Duhr, Falko Dulat, Franz Herzog, and Bernhard Mistlberger. Higgs Boson Gluon-Fusion Production in QCD at Three Loops. Phys. Rev. Lett., 114:212001, 2015.
 - [51] Charalampos Anastasiou, Claude Duhr, Falko Dulat, Elisabetta Furlan, Thomas Gehrmann, Franz Herzog, Achilleas Lazopoulos, and Bernhard Mistlberger. High precision determination of the gluon fusion Higgs boson cross-section at the LHC. JHEP, 1605:058, 2016.
 - [52] Charalampos Anastasiou, Radja Boughezal, and Frank Petriello. Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion. JHEP, 0904:003, 2009.
 - [53] Paolo Nason. A new method for combining NLO QCD with shower Monte Carlo algorithms. JHEP, 0411:040, 2004.
 - [54] Stefano Frixione, Paolo Nason, and Carlo Oleari. Matching NLO QCD computations with Parton Shower simulations: the POWHEG method. JHEP, 0711:070, 2007.
 - [55] Simone Alioli, Paolo Nason, Carlo Oleari, and Emanuele Re. A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP, 1006:043, 2010.
 - [56] Paolo Nason and Carlo Oleari. NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG. JHEP, 1002:037, 2010.
 - [57] M. Ciccolini, Ansgar Denner, and S. Dittmaier. Strong and electroweak corrections to the production of Higgs + 2-jets via weak interactions at the LHC. Phys. Rev. Lett., 99:161803, 2007.
 - [58] Mariano Ciccolini, Ansgar Denner, and Stefan Dittmaier. Electroweak and QCD corrections to Higgs production via vector-boson fusion at the LHC. Phys. Rev. D, 77:013002, 2008.
 - [59] K. Arnold, M. Bahr, Giuseppe Bozzi, F. Campanario, C. Englert, et al. VBFNLO: A Parton level Monte Carlo for processes with electroweak

- bosons. *Comput. Phys. Commun.*, 180:1661, 2009.
- [60] Paolo Bolzoni, Fabio Maltoni, Sven-Olaf Moch, and Marco Zaro. Higgs production via vector-boson fusion at NNLO in QCD. *Phys. Rev. Lett.*, 105:011801, 2010.
 - [61] Ken Mimasu, Veronica Sanz, and Ciaran Williams. Higher order QCD predictions for associated Higgs production with anomalous couplings to gauge bosons. *JHEP*, 08:039, 2016.
 - [62] Tao Han and S. Willenbrock. QCD correction to the $pp \rightarrow WH$ and ZH total cross-sections. *Phys. Lett.*, B273:167, 1991.
 - [63] Oliver Brein, Abdelhak Djouadi, and Robert Harlander. NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders. *Phys. Lett. B*, 579:149, 2004.
 - [64] M.L. Ciccolini, S. Dittmaier, and M. Krämer. Electroweak radiative corrections to associated WH and ZH production at hadron colliders. *Phys. Rev. D*, 68:073003, 2003.
 - [65] Lukas Altenkamp, Stefan Dittmaier, Robert V. Harlander, Heidi Rzehak, and Tom J. E. Zirke. Gluon-induced Higgs-strahlung at next-to-leading order QCD. *JHEP*, 1302:078, 2013.
 - [66] Ansgar Denner, Stefan Dittmaier, Stefan Kallweit, and Alexander Muck. Electroweak corrections to Higgs-strahlung off W/Z bosons at the Tevatron and the LHC with HAWK. *JHEP*, 1203:075, 2012.
 - [67] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 1407:079, 2014.
 - [68] Richard D. Ball et al. Parton distributions for the LHC Run II. *JHEP*, 04:040, 2015.
 - [69] W. Beenakker, S. Dittmaier, M. Krämer, B. Plumper, M. Spira, et al. NLO QCD corrections to $t\bar{t}H$ production in hadron collisions. *Nucl. Phys. B*, 653:151, 2003.
 - [70] S. Dawson, C. Jackson, L.H. Orr, L. Reina, and D. Wackeroth. Associated Higgs production with top quarks at the large hadron collider: NLO QCD corrections. *Phys. Rev. D*, 68:034022, 2003.
 - [71] Yu Zhang, Wen-Gan Ma, Ren-You Zhang, Chong Chen, and Lei Guo. QCD NLO and EW NLO corrections to $t\bar{t}H$ production with top quark decays at hadron collider. *Phys. Lett. B*, 738:1, 2014.
 - [72] S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, and M. Zaro. Electroweak and QCD corrections to top-pair hadroproduction in association with heavy bosons. *JHEP*, 06:184, 2015.

- [73] M. Wiesemann, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, and P. Torrielli. Higgs production in association with bottom quarks. *JHEP*, 02:132, 2015.
- [74] Hung-Liang Lai, Marco Guzzi, Joey Huston, Zhao Li, Pavel M. Nadolsky, et al. New parton distributions for collider physics. *Phys. Rev. D*, 82:074024, 2010.
- [75] Stefan Gieseke, Alberto Ribon, Michael H Seymour, P. Stephens, and Bryan Webber. Herwig++ 1.0: An Event generator for e+ e- annihilation. *JHEP*, 0402:005, 2004.
- [76] J. Bellm et al. Herwig++ 2.7 release note, 2013.
- [77] M. Bähr, S. Gieseke, M.A. Gigg, D. Grellscheid, K. Hamilton, et al. Herwig++ Physics and Manual. *Eur. Phys. J. C*, 58:639, 2008.
- [78] T. Gleisberg, Stefan. Hoeche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert, and J. Winter. Event generation with SHERPA 1.1. *JHEP*, 02:007, 2009.
- [79] ATLAS Collaboration. Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Rev. D*, 83:052005, 2011.
- [80] ATLAS Collaboration. Procedure for the LHC Higgs boson search combination in summer 2011. ATL-PHYS-PUB-2011-011, 2011.
- [81] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J. C*, 71:1554, 2011. Erratum in *Eur. Phys. J. C* 73 (2013) 2501.
- [82] ATLAS Collaboration. Combined search for the Standard Model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Rev. D*, 86:032003, 2012.
- [83] Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. (ATLAS-CONF-2019-021), Jun 2019.
- [84] ATLAS Collaboration. Jet energy measurement and its systematic uncertainty in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Eur. Phys. J. C*, 75:17, 2015.
- [85] ATLAS Collaboration. Electron efficiency measurements with the ATLAS detector using 2012 LHC proton–proton collision data. *Eur. Phys. J. C*, 77:195, 2017.
- [86] ATLAS Collaboration. Electron and photon energy calibration with the ATLAS detector using data collected in 2015 at $\sqrt{s} = 13$ TeV. ATL-PHYS-PUB-2016-015, 2016.
- [87] ATLAS and CMS Collaborations. Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and

- CMS Experiments. Phys. Rev. Lett., 114:191803, 2015.
- [88] ATLAS Collaboration. Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton–proton collision data. JINST, 2018.
 - [89] Jon Butterworth et al. PDF4LHC recommendations for LHC Run II. J. Phys. G, 43:023001, 2016.
 - [90] Iain W. Stewart, Frank J. Tackmann, Jonathan R. Walsh, and Saba Zuberi. Jet p_T resummation in Higgs production at $NNLL' + NNLO$. Phys. Rev. D, 89(5):054001, 2014.
 - [91] Radja Boughezal, Xiaohui Liu, Frank Petriello, Frank J. Tackmann, and Jonathan R. Walsh. Combining Resummed Higgs Predictions Across Jet Bins. Phys. Rev. D, 89(7):074044, 2014.
 - [92] ATLAS Collaboration. Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector. Phys. Rev. D, 90:112015, 2014.
 - [93] ATLAS Collaboration. Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector. Phys. Lett. B, 784:173, 2018.
 - [94] ATLAS and CMS Collaborations. Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV. JHEP, 08:045, 2016.
 - [95] ATLAS Collaboration. Measurements of gluon-gluon fusion and vector-boson fusion Higgs boson production cross-sections in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Lett. B, 789:508, 2019.
 - [96] ATLAS Collaboration. Cross-section measurements of the Higgs boson decaying into a pair of τ -leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Rev., 2018.
 - [97] ATLAS Collaboration. Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector. Phys. Lett. B, 786:59, 2018.
 - [98] ATLAS Collaboration. Measurements of VH , $H \rightarrow b\bar{b}$ production as a function of the vector boson transverse momentum in 13 TeV pp collisions with the ATLAS detector. 2019.
 - [99] ATLAS Collaboration. Search for Higgs bosons produced via vector-boson fusion and decaying into bottom quark pairs in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector. Phys. Rev. D, 98:052003, 2018.
 - [100] ATLAS Collaboration. Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector. Phys. Rev. D,

97:072003, 2018.

- [101] ATLAS Collaboration. Search for the standard model Higgs boson produced in association with top quarks and decaying into a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Rev. D, 97:072016, 2018.
- [102] ATLAS Collaboration. A search for the rare decay of the Standard Model Higgs boson to dimuons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. ATLAS-CONF-2018-026, 2018.
- [103] ATLAS Collaboration. Search for invisible Higgs boson decays in vector boson fusion at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Lett., 2018.
- [104] ATLAS Collaboration. Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Lett. B, 776:318, 2018.
- [105] ATLAS Collaboration. Search for dark matter in events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. JHEP, 10:180, 2018.
- [106] Simone Alioli, Paolo Nason, Carlo Oleari, and Emanuele Re. NLO Higgs boson production via gluon fusion matched with shower in POWHEG. JHEP, 0904:002, 2009.
- [107] Keith Hamilton, Paolo Nason, and Giulia Zanderighi. Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator. JHEP, 1505:140, 2015.
- [108] Stefano Catani and Massimiliano Grazzini. An NNLO subtraction formalism in hadron collisions and its application to Higgs boson production at the LHC. Phys. Rev. Lett., 98:222002, 2007.
- [109] Keith Hamilton, Paolo Nason, Carlo Oleari, and Giulia Zanderighi. Merging $H/W/Z + 0$ and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching. JHEP, 1305:082, 2013.
- [110] Massimiliano Grazzini and Hayk Sargsyan. Heavy-quark mass effects in Higgs boson production at the LHC. JHEP, 1309:129, 2013.
- [111] Gavin Cullen, Nicolas Greiner, Gudrun Heinrich, Gionata Luisoni, Pierpaolo Mastrolia, Giovanni Ossola, Thomas Reiter, and Francesco Tramontano. Automated One-Loop Calculations with GoSam. Eur. Phys. J., C72:1889, 2012.
- [112] Keith Hamilton, Paolo Nason, and Giulia Zanderighi. MINLO: Multi-Scale Improved NLO. JHEP, 10:155, 2012.
- [113] Gionata Luisoni, Paolo Nason, Carlo Oleari, and Francesco Tramontano. $HW^\pm/HZ + 0$ and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO. JHEP, 10:083, 2013.
- [114] S. Frixione, V. Hirschi, D. Pagani, H. S. Shao, and M. Zaro. Weak correc-

- tions to Higgs hadroproduction in association with a top-quark pair. JHEP, 1409:065, 2014.
- [115] S. Dawson, C.B. Jackson, L. Reina, and D. Wackeroth. Exclusive Higgs boson production with bottom quarks at hadron colliders. Phys. Rev. D, 69:074027, 2004.
 - [116] Stefan Dittmaier, Michael Krämer, and Michael Spira. Higgs radiation off bottom quarks at the Tevatron and the CERN LHC. Phys. Rev. D, 70:074010, 2004.
 - [117] Robert V. Harlander and William B. Kilgore. Higgs boson production in bottom quark fusion at next-to-next-to leading order. Phys. Rev. D, 68:013001, 2003.
 - [118] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, Pavel M. Nadolsky, and W. K. Tung. New generation of parton distributions with uncertainties from global QCD analysis. JHEP, 07:012, 2002.
 - [119] Federico Demartin, Fabio Maltoni, Kentarou Mawatari, and Marco Zaro. Higgs production in association with a single top quark at the LHC. Eur. Phys. J. C, 75(6):267, 2015.
 - [120] Stefan Gieseke, Christian Röhr, and Andrzej Siódmok. Colour reconnections in herwig++. The European Physical Journal C, 72(11):2225, Nov 2012.
 - [121] E. Bagnaschi, G. Degrossi, P. Slavich, and A. Vicini. Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM. JHEP, 1202:088, 2012.
 - [122] F. Cascioli, S. Höche, F. Krauss, P. Maierhöfer, S. Pozzorini, and F. Siegert. Precise Higgs-background predictions: merging NLO QCD and squared quark-loop corrections to four-lepton + 0,1 jet production. JHEP, 01:046, 2014.
 - [123] Fabio Cascioli, Philipp Maierhofer, and Stefano Pozzorini. Scattering Amplitudes with Open Loops. Phys. Rev. Lett., 108:111601, 2012.
 - [124] Ansgar Denner, Stefan Dittmaier, and Lars Hofer. COLLIER - A fortran-library for one-loop integrals. PoS, LL2014:071, 2014.
 - [125] Steffen Schumann and Frank Krauss. A Parton shower algorithm based on Catani-Seymour dipole factorisation. JHEP, 03:038, 2008.
 - [126] A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt. Parton distributions for the LHC. Eur. Phys. J., C63:189, 2009.
 - [127] ATLAS Collaboration. Summary of ATLAS Pythia 8 tunes. ATL-PHYS-PUB-2012-003, 2012.
 - [128] ATLAS Collaboration. Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector. Phys. Rev. D, 98:052005, 2018.

- [129] ATLAS Collaboration. Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton–proton collision data. ATLAS-CONF-2016-024, 2016.
- [130] ATLAS Collaboration. Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Phys. Rev. D, 96:072002, 2017.
- [131] ATLAS Collaboration. Measurements of b -jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV. JHEP, 08:089, 2018.
- [132] ATLAS Collaboration. Measurement of the Higgs boson coupling properties in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector. JHEP, 03:095, 2018.
- [133] ATLAS Collaboration. Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV. 2019.
- [134] Christoph Englert, Yotam Soreq, and Michael Spannowsky. Off-Shell Higgs Coupling Measurements in BSM scenarios. JHEP, 05:145, 2015.
- [135] Heather E. Logan. Hiding a Higgs width enhancement from off-shell $gg(\rightarrow h^*) \rightarrow ZZ$ measurements. Phys. Rev. D, 92(7):075038, 2015.
- [136] ATLAS Collaboration. Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Eur. Phys. J. C, 78:293, 2018.
- [137] Alexander L. Read. Presentation of search results: The CL(s) technique. J. Phys., G28:2693, 2002.
- [138] Apollinari G., Béjar Alonso I., Brüning O., Fessia P., Lamont M., Rossi L., and Taviani L. High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1. CERN Yellow Reports: Monographs. CERN, Geneva, 2017.
- [139] Muhammd Ahmad et al. CEPC-SPPC Preliminary Conceptual Design Report. 1. Physics and Detector. 2015.
- [140] ATLAS Collaboration. Projections for measurements of Higgs boson cross sections, branching ratios, coupling parameters and mass with the ATLAS detector at the HL-LHC. ATL-PHYS-PUB-2018-054, 2018.
- [141] Guimarães da Costa et al. CEPC Conceptual Design Report: Volume 2 - Physics and Detector. Technical Report arXiv:1811.10545, Nov 2018.

RESEARCH EXPERIENCE

My current research is on the ATLAS experiment. One of my thesis work is on Higgs coupling measurement with the diphoton channel. I started this project in October, 2015. I took the responsibility to develop VH non-hadronic reconstructed categories. To achieve the goal of balancing the signal sensitivity and a reasonable statistics in those low-stat categories, I performed studies on selecting better reconstructed variables as discriminant variables and investigated into the MC samples used in selection optimization to avoid the overlap at truth stage. Then I conducted data/MC comparison in each category and also validated the signal modeling results. I contributed to generating a part of the final statistical results for publications. In March 2016, the first Moriond conference note [1] was published corresponding to an integrated luminosity 13.3 fb^{-1} collected from 2015 and early 2016. Then, in June 2017, with the additional statistics up to 36.1 fb^{-1} and the optimization of reconstructed categories based on the implementation of “simplified template cross-section”, we published the second EPS conferences note [2] The follow-up paper [3] was published in September, 2018. I contributed to the internal note editing for all of the publications.

Another of my thesis work is the combined measurements of Higgs boson coupling properties using LHC Run2 data. I started this work since November 2017. When the analysis team took the input results containing likelihood models from analysis groups such as $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$ and $H \rightarrow \mu\mu$, I contributed to studies of validating and scrutinizing those single channel results and modifying the input likelihood models with the centrally-handled uncertainties. With a better understanding of the structure and the model details of each Higgs analysis, I developed useful tools to check the uncertainty implementation and to build cor-

relation schemes. When the preparation work was done, I started to generate the combined likelihood models, implement all Higgs coupling (“kappa”) parameterizations, and perform statistical study to produce all the “kappa” results and some of the BSM interpretations. The team published an ICHEP conference note [4] in July 2018, including $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $VH(H \rightarrow bb)$, $H \rightarrow \tau\tau$, $ttH(H \rightarrow \text{Multi-lepton})$, $ttH(H \rightarrow bb)$, and $H \rightarrow \mu\mu$. The follow-up Moriond conference note [5] was published in March 2019, with integrated luminosity updated from channel $VH(H \rightarrow bb)$, and with channels $VBF(H \rightarrow bb)$, $H \rightarrow \text{invisible}$ and $H \rightarrow ZZ(\text{offshell})$ added into the combination. The paper [6] has been submitted. I contributed to the internal note editing for those publications.

Besides, I have taken part in the new physics search, including the ongoing searches for light resonances produced in association with top quarks decay to two hadronic taus (ttX , $X \rightarrow \tau\tau$) starting from February, 2018. I’ve taken the responsibility to generate the signal samples, to help validate the derivation framework selection, to develop MVA for the low-pT $di - \tau$ identification, and also to develop the analysis framework.

As for the performance study, starting from October, 2015, motivated by several excesses in the photon-related channels, I contributed to some basic photon performance studies. The major one I was involved in was getting the photon track isolation cut efficiency scale factors by using single photon samples. The difficulty for the photon track isolation discriminant variable is that the distribution is non-trivial (a large peak at 0, followed by a gap and then a small tail) and can not be fitted with an analytic function. Another issue is that the single photon samples suffer from larger background contamination from jets. I developed a framework to perform the template fit based on the background-enriched control region and used this template in the signal region of tightly identified photons to derive cut efficiency and scale factors. I also maintained the single photon ntuple production used for some other photon identification and isolation studies. The photon track isolation efficiency scale factors, as well as other performance study results, have been used in the high mass diphoton analysis [7] and the photon

performance publication [8] .

Another study I have contributed to as my qualification task starting from winter 2015 is the performance study of several newly-added MDT (Muon Drift Tube) chambers in the ATLAS muon spectrometer at that time. I used the muon calibration stream and the dedicated muon “Tag and Probe” tool to study the reconstructed efficiency and resolution of those MDT chambers based on 13 TeV data. Then the comparison with MC was performed to ensure the suitable detector simulation.

LIST OF PUBLICATIONS

- [1] ATLAS Collaboration. Measurement of fiducial, differential and production cross sections in the $H \rightarrow \gamma\gamma$ decay channel with 13.3 fb^{-1} of 13 TeV proton-proton collision data with the ATLAS detector, ATLAS-CONF-2016-067
- [2] ATLAS Collaboration. Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb^{-1} pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector, ATLAS-CONF-2017-045
- [3] ATLAS Collaboration. Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D 98 (2018) 052005.
- [4] ATLAS Collaboration. Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector, ATLAS-CONF-2018-031
- [5] ATLAS Collaboration. Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector, ATLAS-CONF-2019-005
- [6] ATLAS Collaboration. Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment, Submitted to Phys. Rev. D
- [7] ATLAS Collaboration. Search for new phenomena in high-mass diphoton final states using 37 fb^{-1} of proton-proton collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 775 (2017) 105
- [8] ATLAS Collaboration. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016, Eur. Phys. J. C 79 (2019) 205.

LIST OF TALKS

1. ATLAS Collaboration, “Higgs boson couplings to quarks and leptons at the ATLAS experiment”, International Conference on Kaon Physics, 2019, Perugia, Italy.
2. ATLAS Collaboration, “Combined measurements of Higgs boson production and decay with the ATLAS detector”, The 4th China LHC Physics Workshop, 2018, Wuhan, China.
3. ATLAS and CMS Collaborations, “Measurement of the properties of the SM-like Higgs boson in ATLAS and CMS”, Prospects for Charged Higgs Discovery at Colliders “Charged 18”, 2018, Uppsala, Sweden.
4. Z. Wang et al, “Measurement of Higgs boson production in the diphoton decay channel with the ATLAS experiment”, Division of Particles and Fields meeting, 2017, Fermi National Accelerator Laboratory, USA.
5. Z. Wang et al, “Photon track isolation scale factor study in the ATLAS experiment”, US ATLAS Physics Workshop, 2017, Argonne National Laboratory, USA.
6. Z. Wang et al, “Measurement of Higgs boson production in the diphoton decay channel with the ATLAS experiment”, US ATLAS Physics Workshop, 2017, Argonne National Laboratory, USA.