

A TALE OF A NEW GENERATION

SEARCHING FOR DIMUON DECAYS OF THE HIGGS BOSON
WITH THE ATLAS DETECTOR

Alice Alfonsi



Copyright © 2022 Alice Alfonsi
ISBN: 978-94-6421-639-4

A tale of a new generation

Searching for dimuon decays of the Higgs boson with the ATLAS detector

Thesis, Universiteit van Amsterdam

Cover design: Alice Alfonsi

Printing: Ipskamp Printing



This work has been performed at the National Institute for Subatomic Physics (Nikhef), which is funded by the Dutch Research Council (NWO).

A TALE OF A NEW GENERATION

SEARCHING FOR DIMUON DECAYS OF THE HIGGS BOSON
WITH THE ATLAS DETECTOR

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. ir. K.I.J. Maex
ten overstaan van een door het College voor Promoties ingestelde commissie,
in het openbaar te verdedigen in de Agnietenkapel
op dinsdag 1 maart 2022, te 15.00 uur

door

Alice Alfonsi

geboren te Roma

Promotiecommissie

<i>Promotor:</i>	prof. dr. W. Verkerke	Universiteit van Amsterdam
<i>Copromotor:</i>	dr. L. Brenner	CERN
<i>Overige leden:</i>	prof. dr. A.P. Colijn	Universiteit van Amsterdam
	dr. F. Cerutti	Lawrence Berkeley National Laboratory
	dr. T.A. du Pree	NWO-I Nikhef
	prof. dr. S.C.M. Bentvelsen	Universiteit van Amsterdam
	prof. dr. E. Pallante	Rijksuniversiteit Groningen
	dr. T.R. Pollmann	Universiteit van Amsterdam
	prof. dr. W.J.P. Beenakker	Universiteit van Amsterdam

Faculteit der Natuurwetenschappen, Wiskunde en Informatica

Alla mia mamma.

In loving memory of my father.
As always, I reach for your touch.



CONTENTS

INTRODUCTION	i
1 THEORETICAL FRAMEWORK	1
1.1 The Standard Model	1
1.1.1 The Higgs mechanism	6
1.1.2 Elementary particles	11
1.1.3 Properties of the Standard Model Higgs boson	13
1.1.4 Alternative theories	14
1.2 Standard Model Higgs phenomenology at proton colliders	16
1.2.1 $p - p$ collisions	17
1.2.2 Higgs boson production mechanisms	19
1.2.3 Higgs boson decay channels	21
2 THE LHC AND THE ATLAS DETECTOR	25
2.1 The CERN accelerator complex	25
2.1.1 The Large Hadron Collider	26
2.1.2 Collider parameters	28
2.2 The ATLAS detector	31
2.2.1 Coordinate system and kinematics	32
2.2.2 Tracking system	35
2.2.3 Calorimeter system	36
2.2.4 Muon system	38
2.2.4.1 Outlook on the muon system	39
2.2.5 Trigger system	41
2.2.6 Forward detectors	43
3 EVENT SIMULATION AND PHYSICS OBJECTS	45
3.1 Simulation of physics processes	45
3.1.1 Event generation	46
3.1.2 Detector simulation	48
3.2 Object reconstruction and identification	49
3.2.1 Electrons	53
3.2.2 Photons	55
3.2.3 Jets	56
3.2.4 Muons	58
3.2.4.1 Outlook on muon reconstruction	61
3.2.5 Missing transverse momentum	65
4 SEARCH FOR A HIGGS BOSON IN THE DIMUON CHANNEL	69
4.1 Analysis strategy	69
4.2 Data and Monte Carlo samples	72

CONTENTS

4.2.1	Signal samples	73
4.2.2	Background samples	73
4.2.2.1	High statistics Drell-Yan Monte Carlo samples	74
4.3	Object and event selection	75
4.3.1	Muons	75
4.3.2	Jets	76
4.3.3	Electrons	76
4.3.4	Overlap removal	77
4.3.5	FSR photons	77
4.3.6	Missing transverse momentum	78
4.3.7	Event selection	79
4.4	Event categorisation	80
4.4.1	$t\bar{t}H$ category	81
4.4.2	VH categories	82
4.4.3	VBF and ggF categories	84
4.5	Signal modelling	88
4.6	Background modelling	89
4.6.1	Choice and preparation of the Monte Carlo samples	90
4.6.2	Background model construction	92
4.6.3	Background model selection criteria	94
4.6.4	Stress tests of the background model	98
4.7	Statistical treatment	101
4.7.1	Model building	101
4.7.2	Statistical inference	103
4.8	Results	105
5	CONCLUSION AND OUTLOOK	115
	LIST OF SYMBOLS	119
	LIST OF ACRONYMS	123
	BIBLIOGRAPHY	125
	ACKNOWLEDGEMENTS	137
	SUMMARY	141
	SAMENVATTING	149

INTRODUCTION

The current knowledge about the fundamental constituents of the visible universe is incorporated in a framework called the Standard Model. It is an elegant theory, extensively validated by a large number of experiments, that describes the elementary particles and their interactions, with great accuracy and within a wide energy range. However, its equations are far from providing a complete understanding of nature. The theory is, for example, insufficient to predict the observed fermion masses and their hierarchy, which sees them clustered into three distinct generations.

According to the Standard Model, the Higgs boson is strictly connected to the mechanism responsible for the origin of mass, and thus studying its properties plays a pivotal role in finding further insights. In particular, measuring its interactions with all massive particles is a very precise way to verify if the theory is correct or if there are other, yet unknown processes, at play.

The investigations can be performed by profiting from the highly energetic proton-proton collisions happening at the Large Hadron Collider, which already allowed the historic Higgs boson's discovery in 2012 [1,2]. Thanks to the experimental efforts carried out since then, the interactions of this particle with vector bosons and fermions of the third generation have now been observed, and found to be compatible with the Standard Model. However, those involving first- or second-generation fermions are still elusive, as they give rise to much less probable detectable phenomena. Measuring the Higgs boson's decays into fermion-antifermion pairs is in fact the easiest way to directly probe them, but requires extremely large datasets to compensate for the very low decay rates, which decrease with the masses of the fermions involved.

In the current experimental context, the $H \rightarrow \mu^+ \mu^-$ channel represents the best candidate to perform these studies, offering a clean final state and a branching ratio that is finally becoming accessible with the available data. Comparing the results of its search with the Standard Model's expectations allows to specifically investigate the mechanism behind the origin of fermion masses, as any deviation from the predictions could hint towards the existence of new physics.

This thesis presents a direct search for the $H \rightarrow \mu^+ \mu^-$ decay performed with the ATLAS experiment, using the proton-proton collisions produced during Run 2 of the Large Hadron Collider, at a centre-of-mass energy of 13 TeV.

It is organised as follows:

CHAPTER 1 provides the relevant theoretical background and motivations. It gives a brief introduction to the Standard Model, and summarises the properties of the Higgs boson and its phenomenology at proton colliders, with particular attention to the dimuon decay channel. Alternative theories, attempting to extend

or modify the Standard Model to address the fermion mass patterns, are also discussed.

CHAPTER 2 describes the experimental setup used to perform the $H \rightarrow \mu^+ \mu^-$ search, which consists of the Large Hadron Collider and the ATLAS detector at the CERN accelerator complex. Their performance and timelines are outlined, as well as the upgrades foreseen for the ATLAS muon system in the upcoming high-luminosity phase, when the Standard Model $H \rightarrow \mu^+ \mu^-$ decay is expected to be observed by the ATLAS experiment.

CHAPTER 3 elucidates the procedures used by the ATLAS collaboration to simulate and process data in order to predict, identify and extract information on the physics objects that are important to the $H \rightarrow \mu^+ \mu^-$ analysis. Specific emphasis is given to the reconstruction of muons, and to the novel algorithms that will be employed in the future data-taking periods. In this context, I implemented and validated geometry classes that describe the upgraded muon system, and updated the ATLAS central data format to store effectively the new detector information. Additionally, I developed pattern-finding procedures called *hit recovery* and *segment recovery*, which use precise extrapolations and refits to identify and recuperate possible missed information in the vicinity of a track, improving its quality. To estimate the expected performance, I carried out thorough tests of the updated reconstruction and recovery chain and produced the relevant figures, with the help of simulations that mimic the future behaviour of the muon system.

CHAPTER 4 presents the Run 2 $H \rightarrow \mu^+ \mu^-$ analysis, documenting the procedures with which it selects, classifies and models the $p - p$ ATLAS collision data to search for dimuon decays of the Higgs boson, as well as the statistical treatment that led to the obtained results.

I was active in many parts of this study. In particular, my original work focused on modelling the signal and background contributions, and performing and optimising the procedures used to obtain the final estimates. I developed and maintained a rigorous algorithm that selects the optimal background model in each analysis category, on the basis of background-only and signal-plus-background fits to the data sidebands and to multiple background simulated samples. In this context, I also tested new dedicated Monte Carlo simulations and I prepared them using reweighting and rescaling procedures. Additionally, I performed a full study on the reachable sensitivity with varying background models, fit ranges and binning choices, providing estimations and visualisations of the spurious signal systematic uncertainties that guided the final choice of background models employed in the analysis. I then validated the entire procedure by fitting the chosen models to a large number of alternative simulated samples. All these steps are of critical importance in the search for the rare $H \rightarrow \mu^+ \mu^-$ decay, where background mismodellings at the per-mille level are able to pose a serious bias on the signal.

I also generated the likelihood models used by the analysis team to evaluate the final results and performed likelihood-based signal-plus-background fits to the

observed data, providing estimates of the signal strength and producing all the relevant figures, in each analysis category and in the combined case.

These results have been published in the EPS 2019 conference note [3] and in a paper [4]. I was editor of the internal official documentation accompanying both these publications.

CHAPTER 5 summarises the current knowledge of the Higgs boson's interactions, to which the results presented in this thesis largely contribute. Additionally, the foreseen prospects of the $H \rightarrow \mu^+ \mu^-$ analysis at the Large Hadron Collider and the future achievable sensitivities are discussed.

THEORETICAL FRAMEWORK

The entire visible universe is found to be made only of a few basic building blocks, called elementary particles, whose dynamics are governed by four fundamental forces at the everyday energy scales: the gravitational, the electromagnetic, the strong and the weak force.

Developed in the middle of the XXth century, the Standard Model is still the current most comprehensive theory that describes the elementary particles and their short-range interactions. Nevertheless, its equations are far from providing a complete understanding of nature and many fundamental scientific questions remain unanswered.

The current chapter depicts the main aspects of the Standard Model and gives an overview of the Higgs phenomenology at proton colliders, providing the relevant theoretical background and motivations for the search presented in this thesis.

1.1 THE STANDARD MODEL

The mathematical framework of the Standard Model (SM) is that of a relativistic quantum field theory, that incorporates special relativity and quantum mechanics [5]. The fundamental objects of its formalism are the quantum fields, characterized by operators that define them at all points in space and time. Matter is described in terms of spinor fields, called fermion fields. The forces, on the other hand, are viewed as interactions with vector fields called gauge fields.

The dynamics of a system are defined by the Lagrangian density $\mathcal{L}$. It is a function of the fields, of their derivatives and of the space-time coordinates x_μ that satisfies the Euler-Lagrange equations of motion

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \chi_j)} \right) - \frac{\partial \mathcal{L}}{\partial \chi_j} = 0 \quad \forall j, \quad (1.1)$$

where μ runs from 0 to 3 and labels the space-time coordinates, and each $\chi_j = \chi_j(x_\mu)$ is a fermion or gauge field of the Standard Model. In this and in the following equations, the explicit dependence on the space-time coordinates and

on the fields is suppressed to increase readability, and the Einstein summation convention [6] implies the sum over repeated indices in the same term.

The core structure of the Standard Model is shaped around the concept of symmetry. Indeed, the Lagrangian density is formulated in such a way that it must be invariant under transformations that do not modify the physical system it describes, leaving the equations of motion unchanged. Moreover, Noether's theorem [7] asserts that every continuous symmetry of a physical system corresponds to a conserved quantity, correlating the invariance to measurable properties.

There are two cornerstone types of continuous symmetries in the Standard Model: the global invariance under Poincaré transformations, and the local invariance under gauge transformations. Poincaré transformations consist of translations, rotations and boosts of the inertial reference frame, and global invariance towards them guarantees that a physical system is reference-frame independent. The conserved quantities associated to these transformations are the energy and the momenta of the system.

Gauge transformations represent changes in the specification of the fields. A local gauge transformation U within a given Lie group acts on a generic field as $\chi' = U\chi$ and can be written mathematically as

$$U = e^{iq\zeta^a T^a}, \quad (1.2)$$

where i is the imaginary unit and e is the Euler number, q is a scaling factor considered constant with respect to the space-time coordinates and the T^a are matrices that represent the generators of the group, with the index a running over the group dimension. Each $\zeta^a = \zeta^a(x_\mu)$ is a scalar function of the space-time coordinates that characterises the phase of the transformation and defines it as local, making it act differently on different points of the space-time. Gauge symmetry subsists whenever such transformation leaves the Lagrangian density unchanged, ensuring that the physical laws do not depend on an arbitrary choice of representation for the fields.

The gauge group under which the Standard Model Lagrangian is locally invariant is the twelve-dimensional Lie group

$$SU(3)_C \times SU(2)_L \times U(1)_Y, \quad (1.3)$$

where the subscripts refer to the particular properties of the objects that the different subgroups act upon: $SU(3)_C$ transformations can be written as 3×3 matrices that only act on triplets of matter fields possessing colour charge C , while weak hypercharge Y is the quantity that characterises the $U(1)_Y$ subgroup¹. Lastly, the 2×2 $SU(2)_L$ operators ignore right-handed matter fields, and only interact

¹ Colour charge, analogously to the electric charge Q , indicates the ability to interact with similar charged objects, while weak hypercharge accounts for the flavour content and for the electric charge of a field, according to $Q = T_3 + \frac{1}{2}Y$, where T_3 is the third component of the weak isospin.

with left-handed chirality² L. Right- and left-handed spinor fields, denoted by the symbol ψ , can be represented as singlets and doublets respectively, and written as

$$\begin{pmatrix} \psi \end{pmatrix}_R = \begin{pmatrix} \psi^u \\ \psi^d \end{pmatrix}_L, \quad (1.4)$$

where the labels u and d are used to differentiate the up and down flavour components of the doublet. According to Noether's theorem, conserved quantities must be associated to the generators of each subgroup: invariance under local $SU(3)_C$ transformations conserves the colour charge, while the weak isospin T and the weak hypercharge Y are the quantum numbers that are conserved in $SU(2)_L$ and $U(1)_Y$ respectively.

In the Standard Model, the forces emerge as a direct consequence of the local gauge invariance. Its requirement places some constraints on the Lagrangian density terms that contain the derivative ∂_μ , resulting in the introduction of gauge fields, and of coupling terms involving such fields that ultimately define the interactions, each of them associated with a Standard Model subgroup. In formulae, the generic Lagrangian density that describes a system containing only a free, massless matter field ψ can in fact be written as a purely kinetic term

$$\mathcal{L}_\psi^{\text{kin}} = i\bar{\psi}\gamma^\mu\partial_\mu\psi, \quad (1.5)$$

where $\bar{\psi}$ represents the Dirac adjoint³ of the spinor field and the γ^μ are the Dirac γ -matrices [8]. To preserve the symmetry within a given subgroup of the Standard Model, such that $\mathcal{L}_\psi^{\text{kin}'} = \mathcal{L}_\psi^{\text{kin}}$ under the corresponding local gauge transformation in equation 1.2, the derivative term must be covariant, meaning that it should transform as the field itself. But this is not inherently the case, since the dependence of ζ^a on the space-time coordinates enters the derivation and produces $\partial_\mu\zeta^a$ terms, giving

$$(\partial_\mu\psi)' = \partial_\mu(e^{iq\zeta^a T^a}\psi) \neq U(\partial_\mu\psi). \quad (1.6)$$

The needed invariance can be conveniently restored by replacing ∂_μ with the gauge covariant derivative

$$\mathcal{D}_\mu = \partial_\mu - i\alpha q A_\mu^a T^a, \quad (1.7)$$

where α is a parameter considered constant with respect to the space-time coordinates. To construct such a derivative, it is necessary to introduce the new vector fields A_μ^a , or gauge fields, that transform infinitesimally as

$$A_\mu'^a = A_\mu^a + \frac{1}{\alpha}\partial_\mu\zeta^a + f^{abc}A_\mu^b\zeta^c \quad (1.8)$$

² Chirality is the Lorentz invariant direction, right-handed or left-handed, of the spin of a field.

³ A Dirac adjoint is defined as $\bar{\psi} = \psi^\dagger\gamma^0$, where γ^0 is the time-like gamma matrix and $\psi^\dagger$ is the hermitian adjoint of ψ .

and therefore return $(\mathcal{D}_\mu \psi)' = U(\mathcal{D}_\mu \psi)$. In equation 1.8, f^{abc} are structure constants, antisymmetric in the indices a, b, c , and the indices run over the subgroup dimension: from 1 to 8 in $SU(3)_C$, and from 1 to 3 in $SU(2)_L$, where f^{abc} becomes the totally antisymmetric tensor ϵ^{abc} . In the one-dimensional $U(1)_Y$, the tensor term disappears.

When encapsulating the gauge fields for each Lie subgroup in the covariant derivative $\mathcal{D}_\mu$, in order to have a Lagrangian density that respects the complete Standard Model symmetry, this Lagrangian density no longer only contains the pure kinetic term $\mathcal{L}_\psi^{\text{kin}}$, but it also inherits additional components of the form $\mathcal{L}_{\psi A}^{\text{int}} = \alpha q \bar{\psi} \gamma^\mu A_\mu^a T^a \psi$, one for every set of gauge fields A^a belonging to a given Standard Model subgroup. Such terms connect the gauge fields to the fermion field ψ and are therefore called the coupling, or interaction, terms. They are, in fact, a mathematical description of the known interactions: the fundamental forces in the Standard Model originate naturally from the gauge symmetry of the system, and the parameters α , one for each gauge subgroup, indicate the strength of the corresponding interaction such that, if they were turned off, the Lagrangian density would revert to that of a free spinor field. The α terms, also called coupling strengths, are free parameters of the theory, and their values must be determined through experimental measurements. They generally depend on the energy, and can be considered constant only within a given energy scale. In terms of nomenclature, α_C will be used from now on to indicate the $SU(3)_C$ gauge coupling, while α_L and α_Y refer to $SU(2)_L$ and $U(1)_Y$ respectively.

To complete the picture, it must be noted that the appearance of new gauge fields in the Lagrangian system requires yet another supplementary covariant term, that describes the dynamics of these fields. Such term can be constructed using the field strength tensor

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + \alpha f^{abc} A_\mu^b A_\nu^c, \quad (1.9)$$

where μ and ν run over the space-time coordinates, leading to

$$\begin{aligned} \mathcal{L}_{\text{gauge}} &= -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} \\ &= -\frac{1}{4} (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a) (\partial^\mu A^{\nu a} - \partial^\nu A^{\mu a}) + \\ &\quad -\frac{1}{2} \alpha f^{abc} (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a) A^{b\mu} A^{c\nu} + \\ &\quad -\frac{1}{4} \alpha^2 f^{abc} f^{ade} A_\mu^b A_\nu^c A^{d\mu} A^{e\nu}. \end{aligned} \quad (1.10)$$

The first component in the above summation is a gauge kinetic term $\mathcal{L}_A^{\text{kin}}$, which contains only derivatives of the gauge fields, while the second and third terms represent the self-coupling $\mathcal{L}_{AA}^{\text{int}}$, which connects the gauge fields with themselves. The self-coupling is different than zero only when the subgroup dimension is larger than 1, and so it defines gauge fields in $SU(2)_L$ and $SU(3)_C$ that not only interact with matter, but can also interact among themselves.

Placing together all the required components, the Lagrangian density for a system made of all the Standard Model spinor and gauge fields consists of kinetic terms for all the fields, and of interaction terms that connect the gauge fields with matter and with themselves, i.e.

$$\begin{aligned}\mathcal{L} &= \sum_{\psi, A} i\bar{\psi} (\gamma^\mu \mathcal{D}_\mu) \psi - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \\ &= \sum_{\psi, A} \mathcal{L}_\psi^{\text{kin}} + \mathcal{L}_{\psi A}^{\text{int}} + \mathcal{L}_A^{\text{kin}} + \mathcal{L}_{AA}^{\text{int}},\end{aligned}\tag{1.11}$$

where the summation runs over all the fundamental spinor fields and all the gauge fields in the theory, and where the index a runs over the dimensions of the various subgroups. Using this formalism, the Standard Model is able to elegantly introduce the known fundamental forces that manifest in nature: the $\text{SU}(3)_C$ subgroup defines quantum chromodynamics [9], the theory describing the strong force between colour-charged fields, while the $\text{SU}(2)_L \times \text{U}(1)_Y$ subgroup describes the electroweak interaction [10], a unified force that at energies below ~ 100 GeV breaks down into two distinct manifestations: the long-range electromagnetic force, that involves electric and magnetic charges, and the short-range weak force, responsible for nuclear decay processes. Gravitation fails to be included in the equations, but its magnitude remains negligible at the current experimental scales, thus having no measurable impact.

The same gauge invariance that defines the interactions is also responsible for forbidding explicit mass terms in the Lagrangian density, meaning that all the fundamental fields appearing in equation 1.11 are expected to be massless. In quantum field theory, an explicit mass term for a spinor field ψ is given by the expression

$$\mathcal{L}_{m_\psi} = -m_\psi \bar{\psi} \psi = -m_\psi (\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R),\tag{1.12}$$

where the subscripts R and L refer to right-handed and left-handed chirality respectively. Terms of this form break gauge invariance, as they involve spinors of both chiralities that transform differently under $\text{SU}(2)_L$, such that $\mathcal{L}'_{m_\psi} \neq \mathcal{L}_{m_\psi}$. Meanwhile, the mass term for a generic gauge boson field A_μ reads

$$\mathcal{L}_{m_A} = \frac{1}{2} m_A^2 A_\mu A^\mu\tag{1.13}$$

and under a local gauge transformation as in equation 1.2, it becomes

$$\mathcal{L}'_{m_A} \supset \frac{1}{2} m_A^2 \left(A_\mu^a + \frac{1}{\alpha} \partial_\mu \zeta^a + f^{abc} A_\mu^b \zeta^c \right) \left(A^{a\mu} + \frac{1}{\alpha} \partial^\mu \zeta^a + f^{ade} A^{d\mu} \zeta^e \right)\tag{1.14}$$

being clearly different than $\mathcal{L}_{m_A}$ and thus not invariant under any of the subgroups in $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$. Therefore, the Standard Model does not inherently allow any massive fermion nor gauge field. This contradicts the observed data, as

the gauge mediators of the electroweak interaction, as well as all the elementary fermions, have masses that manifest undeniably in modern experiments.

This discrepancy can only be solved by assuming that mass is not an intrinsic property of the fields themselves but has, instead, an external origin, related to mechanisms that do not involve explicit Lagrangian terms. To achieve this, an additional scalar field is included in the model: the Higgs field. As will be discussed in section 1.1.1, its potential is strictly connected to the electroweak symmetry breaking, motivating the observed independence of the electromagnetic and weak forces at everyday energies. Moreover, its interactions provide the other fields with masses.

In the Standard Model subsists field-particle duality, an abstraction according to which each quantum field can be associated with a physical elementary particle type. A particle represents a quantum excitation of the underlying field with respect to its lower energy state, the vacuum. The elementary particles that constitute matter are called fermions, and are interpreted as quantum excitations of their respective fermion fields. Similarly, the interactions between particles are viewed as exchanges of virtual force carriers called gauge bosons, that constitute the quanta of the gauge fields. The classification in fermions and bosons has its roots in the statistics theorem related to their intrinsic angular momentum, or spin [11]. The elementary fermions have spin $1/2$, and obey the Fermi-Dirac statistics, while the gauge bosons have spin 1 and are governed by the Bose-Einstein statistics. The particle content of the Standard Model will be summarised in section 1.1.2.

1.1.1 *The Higgs mechanism*

The Higgs field is a scalar field that permeates the universe and interacts with all the fundamental fields, including itself. Its potential has a characteristic shape that exhibits a set of degenerate, physically equivalent minima around the origin. Therefore the vacuum expectation value, that is the value of the field that minimises the potential, is different from zero. This has two interesting consequences, grouped under the name Brout-Englert-Higgs mechanism or simply Higgs mechanism, that reconcile the gauge invariance of the Standard Model with the existence of interacting massive fields: on one hand, picking a specific minimum from the degenerate set causes the system to be no longer invariant under rotations, leading to the electroweak symmetry breaking (EWSB) [12–14] that disentangles the electromagnetic and weak effects to result in the observed everyday forces. On the other hand, a vacuum expectation value different from zero influences the dynamics of the Higgs field: while interacting with it, fermion and gauge fields acquire masses that depend on the strength of the interactions and on the vacuum expectation value itself.

These intuitive concepts can be detailed by deriving the relevant mathematical equations. Within the Standard Model’s framework, the Higgs field is described as

a $SU(2)_L$ doublet of complex scalar fields, it does not carry colour charge and has weak hypercharge $Y = 1/2$. It can be expressed as

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \quad (1.15)$$

where $\phi_{1\dots 4}$ are four real scalar fields, and ϕ_+ , ϕ_0 are the complex electrically charged and neutral components of the doublet, respectively.

The Lagrangian density of the Higgs field, fulfilling the Standard Model gauge invariance, is

$$\mathcal{L}_\phi = (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - V(\phi) + \mathcal{L}_{\text{Yukawa}}. \quad (1.16)$$

Here, the first term contains the kinetic component and the interaction terms of the Higgs with the gauge fields, the second term is the potential energy density, and the third term includes the Higgs couplings to fermion fields. The potential density can be written in the most general gauge invariant form as

$$V(\phi) = \lambda(\phi^\dagger \phi)^2 + \mu^2 \phi^\dagger \phi, \quad (1.17)$$

and has its shape entirely determined by the two real parameters λ and μ^2 . The value of λ , which depends on the energy, must remain positively defined up to scales of ~ 100 GeV: this ensures that the potential is bounded from below and that a metastable vacuum exists at everyday energies, as suggested by experimental measurements [15]. On the contrary, there is no such restriction for μ^2 . As shown in figure 1.1, if μ^2 is positive $V(\phi)$ consists of a well centred around its global minimum $|\phi| = \sqrt{\phi^\dagger \phi} = 0$. In this case, the Lagrangian density can be interpreted as that of a scalar field with mass μ that self-interacts through the coupling λ . However, if $\mu^2 < 0$ the potential exhibits a local maximum in the origin and a set of infinite, degenerate minima all around it, defined by

$$\phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = \frac{-\mu^2}{2\lambda}. \quad (1.18)$$

In the Standard Model, this feature represents the premise that makes the Higgs mechanism possible, and thus the Higgs potential is assumed to have $\mu^2 < 0$. Equation 1.18 describes a spherical surface with fixed radius $|\phi| = \sqrt{-\mu^2/2\lambda}$ in the four-dimensional Higgs space, where three independent combinations of $SU(2)_L$ and $U(1)_Y$ gauge transformations can be interpreted as rotations, one for each of the three rotational directions in the Higgs space. The dimensionality of the groups involved also allows for an ulterior independent combination, that is however redundant in a four-dimensional space and therefore does not impact the system.

The existence of multiple minima leads to the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ gauge symmetry. In fact from the local maximum, around which $V(\phi)$ is symmetric, the system spontaneously tends towards a state of minimum energy. In doing so, it picks a particular degenerate state from the existing set of minima. This choice introduces a preferred direction in the ϕ -space that is no

longer preserved by rotations, meaning that the invariance with respect to the corresponding combinations of gauge transformations is lost. The symmetry group of the Standard Model is thus narrowed down to

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} SU(3)_C \times U(1)_{EM} , \quad (1.19)$$

where the strong force described by the $SU(3)_C$ subgroup retains its symmetry as it is not affected by rotations in the Higgs space. Conversely, the electroweak force breaks down into a weak interaction and a purely electromagnetic force. The former has no residual symmetry, since it is associated with the three gauge rotations that alter the system, while the latter is still invariant under the group $U(1)_{EM}$, that corresponds to the redundant $SU(2)_L \times U(1)_Y$ combination that leaves the system unchanged.

In compliance with the combinations of gauge transformations, also the gauge fields $W_\mu^{a=1,2,3}$ of the subgroup $SU(2)_L$ and the field B_μ of $U(1)_Y$ intermix, producing the four independent combinations that represent the gauge fields of the two new forces: the $W_\mu^\pm$ and Z_μ fields

$$W_\mu^+ = \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}} , \quad W_\mu^- = \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}} , \quad Z_\mu = \frac{\alpha_L W_\mu^3 - \alpha_Y B_\mu}{\sqrt{\alpha_L^2 + \alpha_Y^2}} \quad (1.20)$$

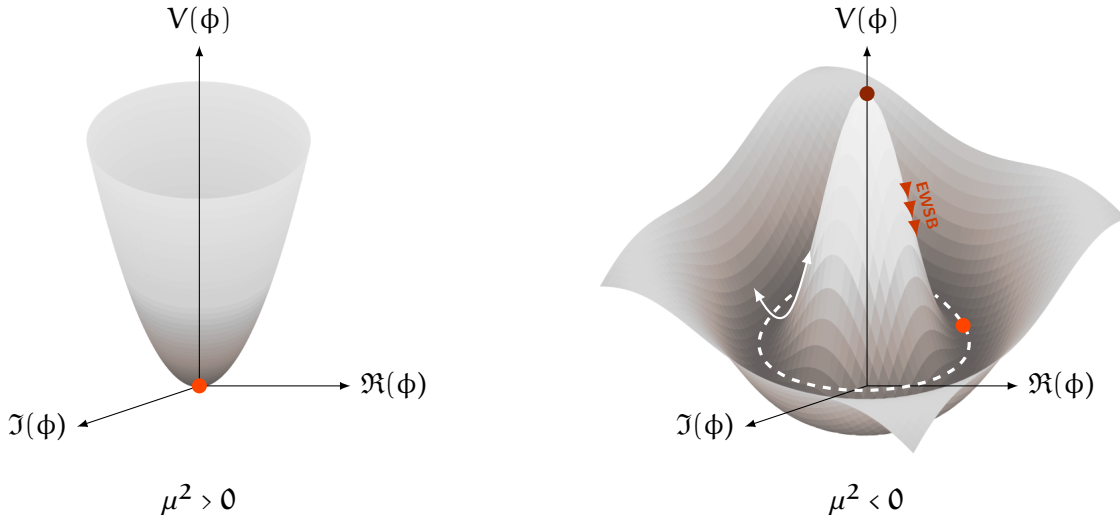


Figure 1.1: Plot of the potential $V(\phi)$ as a function of its real $\Re(\phi)$ and imaginary $\Im(\phi)$ components. On the left, the case with $\mu^2 > 0$, where the orange dot indicates the minimum. On the right the case with $\mu^2 < 0$, that breaks the symmetry as shown by the orange arrows. The brown dot indicates the maximum, while the orange dot is the minimum after symmetry breaking. The dashed curve indicates the set of degenerate minima, and the path of the longitudinal oscillations. The white arrows represents a radial oscillation path.

for the weak interaction, and the photon field

$$\gamma_\mu = \frac{\alpha_Y W_\mu^3 + \alpha_L B_\mu}{\sqrt{\alpha_L^2 + \alpha_Y^2}} \quad (1.21)$$

for the electromagnetic interaction.

Once the symmetry is broken, the Higgs field will still oscillate around the minimum. Longitudinal oscillations along the set of minima experience a flat potential and thus do not require any energy. They can be associated with the production of three massless scalar fields, called Nambu-Goldstone fields [16], one for each rotational direction in the four-dimensional ϕ -space. On the other hand, radial oscillations move towards higher values of $V(\phi)$, and perceive an approximate harmonic oscillator potential that gives rise to a massive scalar field. These four additional scalars emerge directly as an approximation of the Higgs field components, when the oscillations are described through perturbation theory. To apply it, it is first necessary to express ϕ only by means of constant terms and fields with zero expectation values. Without loss of generality, the $\phi_{1,2,3,4}$ can be chosen to be oriented such that their vacuum expectation values are

$$\langle \phi_3 \rangle = v = \sqrt{\frac{-\mu^2}{\lambda}}, \quad \langle \phi_{1,2,4} \rangle = 0, \quad (1.22)$$

and a new real scalar field h with zero expectation value can be introduced as $\phi_3 = h + v$, where v is a constant parameter. The Higgs field becomes

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_4 \end{pmatrix}, \quad (1.23)$$

leading to the perturbative form of the potential

$$V(\phi) = C + 0 \cdot \phi_1^2 + 0 \cdot \phi_2^2 + \lambda v^2 h^2 + 0 \cdot \phi_4^2 + \mathcal{O}(\phi_j^3), \quad (1.24)$$

where C is a constant and where the components involving the fields squared can be interpreted as mass terms: $\phi_{1,2,4}$ are the massless Nambu-Goldstone fields while h has a mass equal to $\sqrt{2\lambda}v$.

It is always possible to choose an appropriate gauge transformation or, in jargon, to fix the gauge, such that ϕ is rewritten as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad (1.25)$$

and is completely characterised just by the field h and by the constant v . This gauge choice is known as unitary gauge, and shows that the Nambu-Goldstone fields are not physical degrees of freedom of the system, since they can be completely removed by means of an arbitrary choice. Based on equation 1.25 it is indeed possible to elaborate an intuitive interpretation of the constant v and of the fields

$\phi_{1,2,4}$ and h . Each scalar $\phi_{1,2,4}$ represents a superfluous degree of freedom that is produced by the symmetry breaking and then reabsorbed by one of the three broken weak gauge fields $W_\mu^\pm$ and Z_μ , which becomes massive in the process. The non-vanishing h , instead, emerges as the only physical Higgs field, which can be observed experimentally as the Higgs boson H . Lastly, v is the only non-zero term that appears in the vacuum expectation value $\langle\phi\rangle$, and is therefore usually referred to as the (physical) Higgs vacuum expectation value.

The mathematical description of how the gauge fields $W_\mu^\pm$ and Z_μ acquire mass is encoded in the Lagrangian term containing the covariant derivatives $(\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi)$ in equation 1.16. When evaluated explicitly, it can be shown to be composed of a pure kinetic term for the field h of the form $\partial_\mu h \partial^\mu h$, of self-coupling and coupling terms with the gauge fields that will be discussed in section 1.1.3, and of a term of the type

$$\begin{aligned} & \frac{v^2}{8} (\alpha_L^2 (W_\mu^1)^2 + \alpha_L^2 (W_\mu^2)^2 + (\alpha_L W_\mu^3 - \alpha_Y B_\mu)^2) \\ &= \frac{v^2}{8} (2\alpha_L^2 W_\mu^+ W^{-\mu} + (\alpha_L^2 + \alpha_Y^2) Z_\mu^2) , \end{aligned} \quad (1.26)$$

where the second line uses equation 1.20 and equation 1.21 to introduce the weak and electromagnetic gauge fields. This formula can be read as the sum of the mass terms for the gauge fields $W_\mu^\pm$ and Z_μ , where the masses are

$$m_W = \frac{\alpha_L v}{2} , \quad m_Z = \frac{v \sqrt{\alpha_L^2 + \alpha_Y^2}}{2} . \quad (1.27)$$

The photon field γ_μ , on the other hand, does not appear in the equation and remains therefore massless, as well as the $SU(3)_C$ gauge fields that are not affected by the Higgs mechanism at all. To summarise, the gauge fields that describe the observed electromagnetic and weak interactions derive naturally from the spontaneous symmetry breaking, and obtain mass as a direct consequence of the existence of an interacting Higgs field with vacuum expectation value different than zero.

Fermion fields do not appear as a byproduct of the symmetry breaking, and to acquire mass they require the additional component $\mathcal{L}_{\text{Yukawa}}$ in the Higgs Lagrangian density, which can be constructed to be invariant under $SU(2)_L \times U(1)_Y$ transformations as

$$\mathcal{L}_{\text{Yukawa}} = \sum_{\psi, d, u} -y_d \bar{\psi}_L \phi \psi_R^d - y_u \bar{\psi}_L \tilde{\phi} \psi_R^u + \text{h.c.} \quad (1.28)$$

and consists of two parts, related to down type and up type fermion fields respectively. The abbreviation h.c. indicates hermitian conjugation, and the summation runs over all the possible left-handed $SU(2)_L$ doublets ψ_L and right-handed singlets

of up (ψ_R^u) and down (ψ_R^d) type⁴. The term $\tilde{\phi} = i\sigma_2\phi^*$, with σ_2 a Pauli matrix and ϕ^* the charge conjugate of ϕ , is the antidoublet of the Higgs field, while y_d and y_u are free parameters called Yukawa coupling strengths.

The physical meaning of y_d and y_u can be explained by expanding $\mathcal{L}_{\text{Yukawa}}$ in terms of the explicit expression of the Higgs field in the unitary gauge shown in equation 1.25, and of the left-handed and the right-handed fields in equation 1.4. The down-type part of $\mathcal{L}_{\text{Yukawa}}$ becomes

$$\mathcal{L}_{\text{Yukawa}^d} = -\frac{y_d v}{\sqrt{2}} \bar{\psi}^d \psi^d - \frac{y_d}{\sqrt{2}} h \bar{\psi}^d \psi^d, \quad (1.29)$$

where $\bar{\psi}_L^d \psi_R^d + \bar{\psi}_R^d \psi_L^d = \bar{\psi}^d \psi^d$ was used. The first term gives mass to the field ψ^d , where

$$m_d = \frac{y_d v}{\sqrt{2}}, \quad (1.30)$$

and the second term is the interaction of ψ^d with the Higgs field. Since the Yukawa terms for up and down components behave identically, the expansion leads to the exact same formulae for the up-type fields when substituting ψ^d with ψ^u , and the generic ψ with Yukawa coupling y_ψ can be used without loss of generality.

As in the case for gauge fields, although through a different procedure, the existence of a Higgs field with non-zero vacuum expectation value is the means by which fermion fields acquire mass. The Standard Model fixes completely the mathematical form of all the mass terms, both for fermion fields and gauge fields, but it does not say anything about the mass values, which need to be extrapolated by experimental measurements.

1.1.2 Elementary particles

The particle content of the Standard Model consists of a set of non-composite, or fundamental, fermions and bosons.

According to the way they behave with respect to the Standard Model interactions, fermions can be divided into two groups of six particles each: leptons and quarks, both having spin 1/2. All quarks interact electromagnetically, strongly and weakly. Leptons, instead, do not take part in strong interactions. They can be electrically charged and interact electromagnetically and weakly, or they can be neutral particles, called neutrinos, only experiencing the weak force. For each fermion a correspondent antifermion exists, which is associated to the Dirac adjoint $\bar{\psi}$ and has the same mass of its counterpart, but the opposite quantum numbers.

As shown in table 1.1, both quarks and leptons exist in six flavours, each one with different properties. Moreover, they can be grouped into three generations, each one including two quarks and two lepton flavours: the electron (e), the

⁴ Currently it is not known if neutrino fields are Dirac fields. In this case, they could acquire mass through the Yukawa interaction for up-type Dirac fermions. Alternatively, a different mechanism must be provided.

	Leptons			Quarks		
		Q [e]	m [MeV]		Q [e]	m [MeV]
First generation	e	-1	0.51	u	+2/3	2.16
	ν_e	0	$< 1.10 \times 10^{-6}$	d	-1/3	4.67
Second generation	μ	-1	105.66	c	+2/3	1.27×10^3
	ν_μ	0	< 0.19	s	-1/3	93.00
Third generation	τ	-1	1.78×10^3	t	+2/3	172.76×10^3
	ν_τ	0	< 18.20	b	-1/3	4.18×10^3

Table 1.1: The fundamental fermions included in the Standard Model. For each particle the electric charge Q in electron units and the most recent measured values, or limits, for the masses m are reported [17].

Boson	Interaction	Q [e]	m [MeV]
γ	Electromagnetic	0	$< 1 \times 10^{-24}$
Z	Weak	0	91.19×10^3
$W^\pm$	Weak	± 1	80.38×10^3
g	Strong	0	0

Table 1.2: The Standard Model gauge bosons. For each particle the electric charge Q in electron units and the most recent measured values, or limits, for the masses m are reported, with the exception of the gluon mass that is a theoretical value [17].

electron neutrino (ν_e), the up (u) quark and the down (d) quark belong to the first generation, the muon (μ), the muon neutrino (ν_μ), the charm (c) quark and the strange (s) quark form the second generation and the tauon (τ), the tau neutrino (ν_τ), the top (t) and the bottom (b) quarks characterise the third generation. Every generation appears to be an exact copy of the other two, with the only difference residing in the observed masses of the particles in it. In particular the masses of charged fermions, which can be measured very precisely, increase significantly with the generation, seemingly following an underlying pattern that spans from the few MeV of the first generation to the thousand MeV of the third generation.

All gauge bosons have spin 1. As illustrated in table 1.2, they are of different types, depending on the force that they mediate. The electromagnetic interaction is carried by the photon (γ), the weak interaction is associated to the Z and W bosons, and the gluons (g) carry the strong interaction. Photon and gluons are massless, while the Z and W bosons are massive. The Z boson, the photon and the gluons are electrically neutral, while the W boson comes in two variants, W^+ and W^- , with positive and negative electric charge respectively. The gluons come in eight variants, each one with a unique colour charge.

The last element in the Standard Model's pool is the Higgs boson H : it is the only known fundamental scalar particle, having spin 0, and is the quantum of the Higgs field.

1.1.3 Properties of the Standard Model Higgs boson

The Standard Model Higgs boson is a scalar particle with spin 0, and with even combined charge conjugation and parity (CP). Its mass is a free parameter of the theory given by the equation

$$m_H = \sqrt{2\lambda v^2}, \quad (1.31)$$

where λ is the self-coupling term that appears in the Higgs potential of equation 1.17 and v is the expectation value of the Higgs field h , calculable as

$$v = \sqrt{\frac{1}{\sqrt{2}G_F}} \sim 246.22 \text{ GeV} \quad (1.32)$$

using the Fermi constant $G_F = 1.166 \times 10^{-5}$, which is determined very precisely from muon decay experiments [18].

The strength of the interactions of the Higgs boson with the other fundamental particles is proportional to the masses of these particles, meaning that heavier particles couple more intensely to it. More precisely, the coupling to gauge bosons is proportional to the square of their mass, while that to charged fermions varies linearly with the fermion mass. The entirety of the Higgs couplings can be summarised by the Lagrangian density

$$\begin{aligned} \mathcal{L}_H^{\text{int}} = \sum_{\psi, V} & -\alpha_{H\psi\bar{\psi}} \bar{\psi}\psi H + \delta_V V_\mu V^\mu \left(\alpha_{HVV} H + \frac{\alpha_{HHVV}}{2} H^2 \right) \\ & + \frac{\alpha_{HHH}}{6} H^3 + \frac{\alpha_{HHHH}}{24} H^4, \end{aligned} \quad (1.33)$$

where the sum is extended to all the fermions ψ of the Standard Model, and where V stands for the vector boson $W^\pm$ or Z . Reading from left to right, the first term encodes the interaction of the Higgs boson with fermions, where

$$\alpha_{H\psi\bar{\psi}} = \frac{m_\psi}{v} \quad (1.34)$$

is the corresponding strength. The second term represents the Higgs couplings with the weak gauge bosons, where

$$\alpha_{HVV} = \frac{2m_V^2}{v}, \quad \alpha_{HHVV} = \frac{2m_V^2}{v^2} \quad (1.35)$$

are the relative strengths, and where $\delta_{V=W,Z}$ assumes the value $\delta_W = 1$ or $\delta_Z = 1/2$. The Higgs boson's coupling to gluons and photons is only induced indirectly via

loop processes that involve intermediate massive quarks or boson fields. Lastly, the Higgs boson can interact with itself, and

$$\alpha_{HHH} = \frac{3m_H^2}{v}, \quad \alpha_{HHHH} = \frac{3m_H^2}{v^2} \quad (1.36)$$

are the trilinear and quartic self-coupling strengths, respectively.

As with the mass terms that result from the Higgs mechanism described in section 1.1.1, the mathematical form of all the Higgs interactions with the other fundamental particles is completely fixed by the Standard Model. However, there is no prediction regarding the coupling strengths themselves, which need to be measured experimentally. These strengths manifest in the rates at which the Higgs interactions happen, therefore all the possible interactions must be investigated. At the same time, given the dependence of the couplings on the masses, very precise mass measurements of all the fundamental particles are also needed to test if the relationships in equations 1.34–1.36 hold.

1.1.4 *Alternative theories*

The Standard Model is an elegant theory, whose predictions have been extensively tested by a large number of experiments throughout the years, proving its effectiveness in describing physics phenomena with great accuracy and within a wide energy range [19]. However, some experimental phenomena and theoretical shortcomings cannot be explained within its current framework, suggesting that it is not a conclusive model of fundamental physics, but only the effective representation of a much larger theory [20].

From a theoretical point of view, the inability to incorporate gravity in terms of quantum fields is already a severe limitation, meaning that the Standard Model is indeed insufficient to predict physics at energies around the Planck scale⁵, where gravitational effects become significant. Another theoretical weakness concerns the mass of the Higgs boson. Its physical value is affected by very large contributions coming from radiative corrections to the Yukawa interactions, which must be fine-tuned very precisely in order to obtain the mass value that is measured experimentally. This ad-hoc tuning could be avoided under the assumption of undiscovered physics symmetries or processes that are not prescribed by the Standard Model [21].

There are also a number of experimental observations that the theory cannot explain at all. For example, the detection of cosmological phenomena such as the cosmic microwave background radiation indicates that the known matter and antimatter particles only add up to about 5% of the total content of the universe. A remaining 24% is attributed to the so-called dark matter, made of mostly gravitationally interacting particles, while another 71% should be dark energy, an unknown energy density that permeates the whole universe [22]. The Standard Model does not supply any eligible dark matter nor dark energy candidate.

⁵ The Planck scale corresponds to energies of the order of $M_P \sim 10^{19}$ GeV.

Additionally, no Standard Model mechanism is able to account for the strong measured matter-antimatter asymmetry in the universe, which is of the order of $\sim 10^{-10}$ when expressed in terms of the dimensionless net baryon to photon ratio [23]. Processes that violate the combined charge conjugation and parity symmetry could potentially cause the imbalance, but the predicted effects are not sufficiently large in the Standard Model, and could only be explained by the existence of new physics [24].

Another inconsistency is related to neutrinos. The Standard Model introduces them as massless, but the experimental observation of solar and atmospheric neutrino flavour oscillations contradicts this assumption [25, 26]. Although neutrino masses could be accommodated in the Standard Model with an apposite mechanism that is possibly different than the Yukawa interaction [27], to this day the exact mass values of these particles are still unknown, and their experimental measurement is one of the major pending issues in modern particle physics.

In general, the mass generation mechanism in the Standard Model is insufficient to properly explain the measured fermion masses. The peculiar hierarchy that orders fermions into three generations seems to follow some natural rule that the theory, treating the masses as free parameters, is not able to justify. It is not known why each fermion has a given mass, why fermions cluster into generations spaced in mass and why the top quark, the heaviest particle, has a mass approximately equal to the vacuum expectation value of the Higgs field. It is thus reasonable to wonder if the Yukawa mechanism itself is complete, and if it is just part of a more complex scheme.

During the last decades, various attempts were made at building models that can address the fermion masses in an exhaustive way. Most of these models stem from the hypothesis of a larger gauge symmetry group, that extends the Standard Model and spontaneously breaks to give back $SU(3)_C \times SU(2)_L \times U(1)_Y$. Starting from the observation of the mass patterns, these theories propose scenarios where the additional symmetry prohibits most of the quark and lepton masses, that can thus only be generated via radiative loop processes [28]. Some assume that the top quark is the only fermion acquiring mass at tree-level, following the Standard Model Yukawa prescription [29]. Such theories are motivated by the bulkiness of this quark, which has a Yukawa coupling very close to 1. The remaining fermion masses are interpreted as higher-order corrections, in which loops of virtual top quarks indirectly expose the other fermions to the Higgs field, giving them lighter masses based on the different loop orders. This indirect exposure is mediated by new force fields that couple the top quark to the other fermions. Other theories extend the previous argument and suggest that the whole third generation of fermions interacts with the Higgs field according to the Standard Model Yukawa mechanism, and that only the masses of the second and first generations are acquired through radiative corrections, which involve the exchange of exotic gauge particles with the third generation following one-loop and two-loop processes respectively [30, 31].

The topic gained renewed interest in the past year, as a result of the growing experimental possibilities that allow to explore the fermion sector with increased sensitivities. Different types of exotic force carriers are being investigated, all with

masses substantially heavier than the currently measurable scale, such that they went undetected until now. These exotic fields could then easily be included into supersymmetric theories [32] or composite Higgs models [33]. Nevertheless, all hypotheses remain only speculative so far, awaiting experimental input. One solid evidence that could support or distinguish between them is the eventual discovery of the predicted exotic particles.

In the meantime, it is critical to test the Standard Model predictions, as any statistically significant discrepancy between the measured and theoretically predicted values would also hint towards the existence of new physics. In particular, establishing the Yukawa coupling of at least one fermion of the second generation is a very clear way to verify whether the Yukawa interaction has a major role in the mass generation or if there are other, yet unknown processes, at play.

1.2 STANDARD MODEL HIGGS PHENOMENOLOGY AT PROTON COLLIDERS

Hadron colliders are an essential tool in testing the Standard Model. In particular, $p - p$ colliders are able to generate two highly energetic proton (p) beams and direct them to meet head-on. Hadrons are composite particles whose constituents are free to interact and rearrange as a result of collisions, potentially giving rise to new particles. According to the theoretical predictions, a possible outcome of a $p - p$ collision leads to a Higgs boson, which can be produced together with a variable number of accompanying particles X , according to the reaction $pp \rightarrow H + X$. However, an event like this is rare when compared to the large number of concurrent interactions that happen when the two beams meet. Such processes generate many different objects that can mimic and hide the presence of a signal coming from the Higgs boson, constituting the background.

Collisions are treated as statistical processes. The Higgs production cross section σ_H , which is the probability to obtain a Higgs boson, depends on the energy of the collision and on the mass of the boson itself. Moreover, the Higgs is an unstable particle and it disintegrates shortly after being produced, generating a set of experimentally detectable objects that can be used to reconstruct the original signal. The available decay final states and their likelihood to occur, given by the branching ratio (BR), depend on the kinematic properties of the decay process, on the mass of the Higgs boson and on the strength of its couplings to the other particles involved. Since the Higgs couplings are proportional to the masses, heavier decay products are favoured.

The Large Hadron Collider (LHC), the current highest energy collider detailed in chapter 2, started running in 2008 and was built to investigate the existence of the Higgs boson as one of its main goals. Using the LHC data, in the summer of 2012 the ATLAS and CMS experiments announced the discovery of a new particle with mass of approximately 125 GeV, compatible with the Standard Model Higgs boson [1, 2] and marking a historic milestone in particle physics. Further studies throughout the following years probed many characteristics of this particle, and found yet no deviations from the Standard Model. The measured spin and parity,

as well as the production and decay rates are all consistent with the theoretical predictions. However, tiny unpredicted effects could have been imperceptible with the past sensitivities.

The increasing amounts of data produced at the LHC allow to perform measurements with unprecedented precision, and to study processes that remained inaccessible until now, such as the Yukawa interactions of the Higgs boson with light fermions. While the couplings with charged leptons and quarks of the third generation have been already measured and shown to follow the Standard Model, the second and the first generations could potentially lead to discrepancies. It is of crucial importance to test them, in order to verify the mass generation mechanism. In particular, second-generation fermions have intermediate mass values, and therefore intermediate Yukawa couplings to the Higgs field, and can be already within experimental reach.

1.2.1 $p - p$ collisions

At high energy colliders, hadrons can undergo different kinds of processes, broadly classified as either hard or soft scatterings and described by quantum chromodynamics (QCD).

The hard scattering involves large momentum transfers and can be described perturbatively, since at high energies the strong coupling parameter α_C is small [34]. Any observable σ can thus be written as a series $\sigma = \sigma_0 + \sigma_1 \alpha_C + \sigma_2 \alpha_C^2 + \dots$, and the hard collision can be explained using an intuitive theoretical picture called the parton model. Within its context, the hadrons are composed by a multitude of quarks, antiquarks and gluons, collectively known as partons.

The quarks and antiquarks that determine a hadron's quantum numbers are called valence quarks. For example, a proton consists of two u and one d valence quarks. In addition, these partons are surrounded by a sea of virtual particles that is overall neutral and does not participate in determining the properties of the hadron, but is characterised by a continuous exchange that involves processes such as gluon splitting into quark-antiquark pairs, counterbalanced by their consequent recombination [35].

Thanks to the binding force becoming weaker with increasing energy, at high momenta partons can move independently and freely within the hadron, according to a unique property called asymptotic freedom [36]. Therefore, the hard scattering can be interpreted as an interaction between the point-like constituents of the colliding hadrons. Each parton can be considered as carrying a fraction p_j of the hadron momentum P . This fraction is represented by the Bjorken-Feynman scaling variable $x_j = 0, \dots, 1$, such that the momentum of the parton can be expressed as $p_j = x_j P$. The allocation of a hadron momentum among its internal constituents is not known a priori, and at a given momentum transfer Q it can be parametrised by the parton distribution functions (PDFs) $f_j(x_j, Q^2)$, which represent the probability density for finding a parton with a certain fraction x_j of the total momentum. Typical hard scattering interactions are those producing massive objects, like top quarks and Higgs bosons, and eventually jets, which are streams of particles

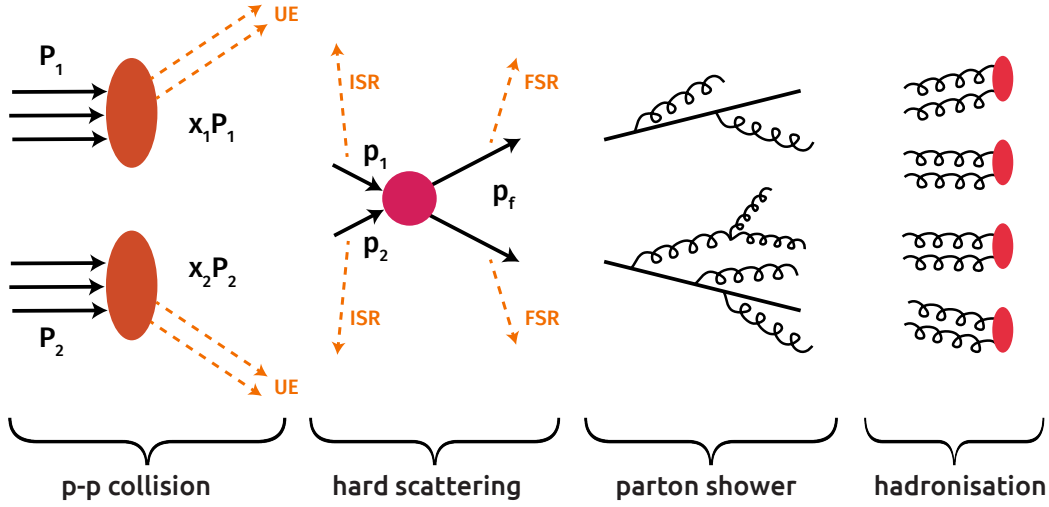


Figure 1.2: Schematic summary of the subsequent processes that take place during a $p - p$ collision.

grouped in cones of a given aperture around a certain direction. These hard scattering processes are rare and represent only a tiny fraction of the entirety of events happening during a beam crossing.

The more likely soft scattering, on the other hand, involves low momentum transfers and requires a non-perturbative treatment due to larger values of α_C , that increases at lower energies. As a consequence, soft scattering processes are mostly not calculable. Examples of soft scattering are the activity carried out by the remnants of a disintegrated hadron, or the multi-parton interactions. In collider physics such phenomena are categorised as part of an underlying event (UE), that includes any process happening concurrently to a hard collision but not originating directly from it. Another example of soft scattering is the parton showering (PS), consisting of a chain of parton branchings that result in a cascade of particles. The soft scatterings can be studied using a variety of simplified models, but there is as of yet no convincing theoretical computation that is able to fully single out and calculate them [37], and a description of these effects is only possible with the help of experimental data, which are used to tune the parameters.

A $p - p$ collision usually takes place following a series of subsequent steps, shown in figure 1.2, that involve both perturbative and non-perturbative calculations. When two protons with momenta P_1 and P_2 approach each other at high energies, they can effectively be described as a collection of partons distributed according to the relevant PDFs, and an incoming parton from each proton typically enters the hard scattering. If the PDFs of the two incoming partons are $f_1(x_1, Q^2)$ and $f_2(x_2, Q^2)$, the effective energy available for the interaction is defined as $\sqrt{\hat{s}} = \sqrt{s} x_1 x_2$, with $\sqrt{s}$ the centre-of-mass energy of the collision and $x_{1,2}$ the Bjorken-

Feynman variables associated with the two partons. The total hadronic cross section can then be calculated as

$$\sigma_{P1,P2 \rightarrow F} = \sum_{1,2} \int dx_1 dx_2 f_1(x_1, Q^2) f_2(x_2, Q^2) \tilde{\sigma}_{x_1, x_2 \rightarrow F}, \quad (1.37)$$

where F is a final state and $\tilde{\sigma}$ is the cross section of the hard scattering calculated at parton level.

The hard process may produce a short-lived resonance $\mathcal{R}$ with mass $m_{\mathcal{R}} \leq \sqrt{s}$ that decays in a number of detectable products. As a consequence of the large momentum transfer that characterises the hard collision, the resulting decay products generally have momenta very far off in the transverse direction, where they can be easily detected. On the contrary, the remnants of the disintegrated protons proceed along the beam line. These particles might engage in further semi-hard or soft interactions, generating low momentum objects. Alternatively, they can branch producing gluon-antiquark ($\bar{q}g$), quark-antiquark ($q\bar{q}$) or gluon-gluon (gg) pairs that in turn give rise to further radiation, resulting in parton showers that crowd the longitudinal direction.

Both the ingoing and outgoing high momentum partons are also able to initiate a sequence of branchings before and after participating in the hard scattering, building up the initial-state radiation (ISR) and the final-state radiation (FSR) respectively. Additionally, charged decay products from the resonance $\mathcal{R}$ can radiate photons that contribute further to the FSR. At lower momenta the coupling parameter α_C becomes extremely strong, so the large number of quarks and gluons resulting from the showering recombine into bound states, or hadronise, forming hadrons that cluster around the direction of the original parton, and which can then be detected as jets.

Overall, a possible final state for a single $p - p$ collision includes a resonance and a variable series X of other particles. At a hadron collider, the protons within the beams are grouped together in bunches, in order to maximise the chances of hard collisions. When two bunches cross in what is called an event, many concurring $p - p$ interactions happen, involving different protons in the bunches. Given the rarity of the hard scattering processes, most of these interactions are soft, and are referred to as in-time pile-up collisions. Identifying the hard collision of interest among them is very challenging, and requires specialised techniques.

1.2.2 Higgs boson production mechanisms

As shown in figure 1.3, a Higgs boson can be produced through a number of different mechanisms, called production modes, each one with a different cross section and with distinct features that can help distinguishing the Higgs signal from the background events.

For a collision energy of $\sqrt{s} = 13$ TeV, corresponding to the maximum energy currently available at proton colliders, and a Higgs mass of approximately 125 GeV, the most abundant production mode is gluon fusion (ggF). In this process the

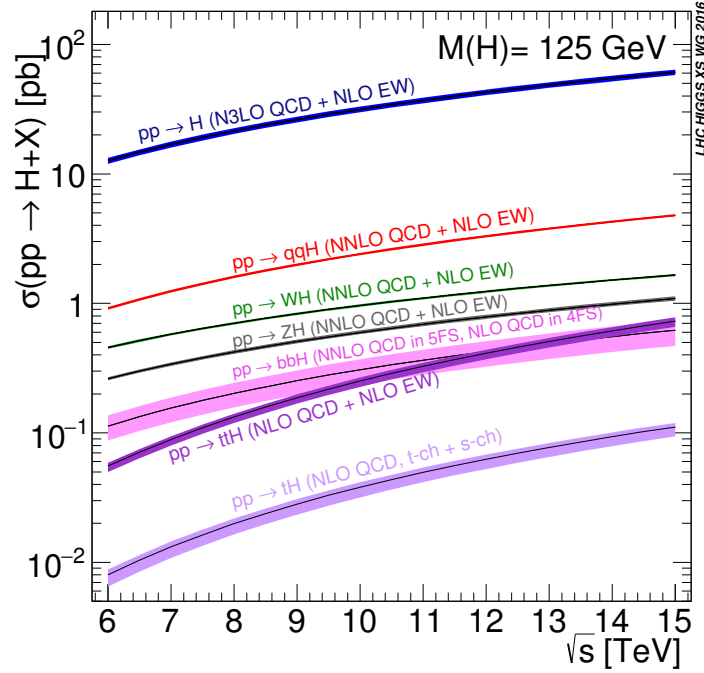


Figure 1.3: The Standard Model Higgs boson production cross sections as a function of the centre of mass energy of the $p - p$ collisions, $\sqrt{s}$. The coloured bands indicate the calculation theoretical uncertainties, and the curves are evaluated for $m_H \sim 125$ GeV [38].

Higgs boson arises from a loop of virtual heavy quarks, mainly top quarks, that result by the fusion of two gluons. Contribution from lighter quarks are suppressed, as their coupling to the Higgs boson decreases proportionally to their mass. At leading order only a single Higgs boson is produced, but first- and second-order QCD radiation can result in additional jets.

The second most abundant production mode is called vector boson fusion (VBF, or qqH). Here, the Higgs boson is produced as a result of the scattering of two quarks, mediated by the exchange of a virtual $W^\pm$ or Z boson. The Higgs boson is radiated by the weak boson propagator, while the scattered quarks give rise to an additional pair of jets in the final state. The two jets are highly energetic and are directed in opposite directions along the proton beam line, whereas the Higgs boson is more centrally located. This constitutes a distinctive signature that is very useful for isolating the Higgs signal.

Another important production mechanism, having the third largest cross section, is the Higgs-strahlung (VH) where the Higgs boson is radiated by a $W^\pm$ or Z boson that originates from the annihilation of a quark-antiquark pair. The radiating vector boson is also present in the final state, providing a handle towards a cleaner signal environment.

Finally, the Higgs boson can also be produced in association with a pair of heavy quarks. In particular, the top fusion mechanism ($t\bar{t}H$) sees a top-antitop pair originating from QCD interactions, which fuses radiating a Higgs particle.

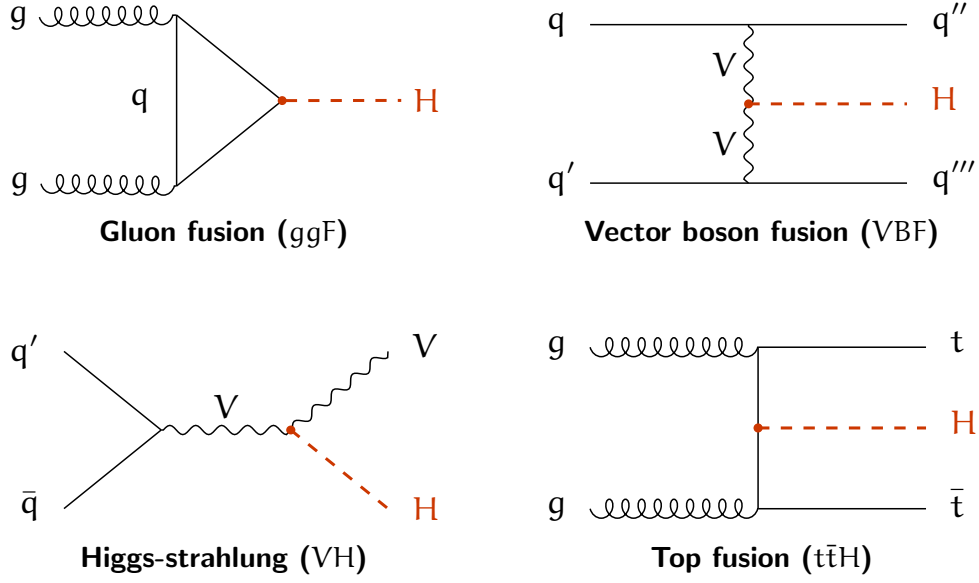


Figure 1.4: Feynman diagrams for the main Higgs boson production modes at the leading order, where q , q' , q'' and q''' indicate generic quarks and $V = W^\pm$ or Z .

Although this production mode has a much lower cross section, it retains a large experimental interest thanks to its ability to probe the coupling of top quarks to the Higgs boson directly, without loop processes. The experimental identification of this production mode is aided by the abundant bottom quarks in the final state, largely originating from top quark decays.

There is a number of additional mechanisms that can result in Higgs bosons, which involve associated production to a single top quark (tH) or a pair of bottom ($b\bar{b}H$) or charm quarks. They have lower cross sections, but could in principle still be able to provide valuable information regarding the Yukawa couplings. The Feynman diagrams corresponding to all the main production modes described in this section are shown in figure 1.4.

1.2.3 Higgs boson decay channels

As shown in figure 1.5, a Higgs boson mass of about 125 GeV grants access to a reasonable number of decay channels, with a sufficient branching ratio to be detected experimentally. The dominant final state is by far given by $H \rightarrow b\bar{b}$, with branching ratio $\text{BR}(H \rightarrow b\bar{b}) \sim 58\%$, followed by the decay to a pair of $W^\pm$ bosons $H \rightarrow W^+W^{*-}$, where one of the vector bosons is produced off-shell to respect the kinematics, as from energy conservation it must be $m_H \geq 2m_{W^\pm}$. The Higgs boson can also decay into a pair of massless particles, photons and gluons, through loops of virtual top quarks and $W^\pm$ bosons, where the high mass of these particles compensates for the generally smaller amplitude of the loop processes. Other relevant decay channels are $H \rightarrow \tau^+\tau^-$, $H \rightarrow c\bar{c}$ and $H \rightarrow ZZ^*$, whose branching ratios are reported in table 1.3.

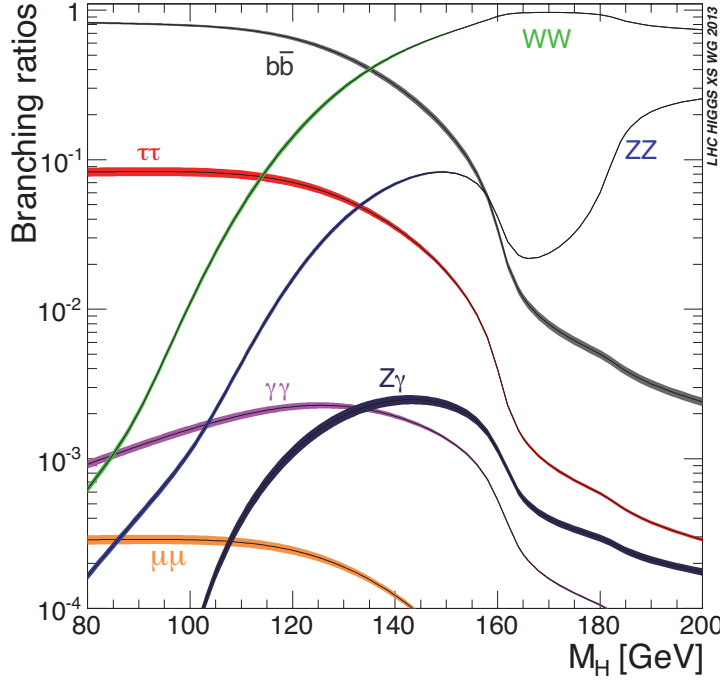


Figure 1.5: Standard Model predictions for the decay modes of the Higgs boson as a function of its mass. The coloured bands represent the theoretical uncertainties.

The probability of observing a given final state comes from a trade-off between the decay branching ratio and the experimental capability to detect the decay products, which depends on the topology of the signal and on how easily it can be isolated from the background. For example, studying a final state with hadronic content such as $H \rightarrow b\bar{b}$ is very challenging as its sensitivity, despite the large branching ratio, is limited by the presence of a large multi-jet background from soft parton scattering and requires advanced techniques to be suppressed. In contrast, the much less probable decay mode $H \rightarrow ZZ^*$ is considered a golden channel in terms of Higgs searches, since its purely leptonic decay products guarantee a very clean and easily identifiable final state against the overwhelming QCD background, giving very high sensitivities even if the branching ratio is only $\sim 3\%$.

Measuring the rates of the Higgs boson decays into fermion-antifermion pairs is the easiest way to directly probe the Yukawa couplings, which manifest at tree level in the decay processes as shown by the Feynman diagram in figure 1.6 for the $H \rightarrow \mu^+\mu^-$ case. An exception concerns the top and bottom quarks, whose couplings can also be measured thanks to the $t\bar{t}H$ and $b\bar{b}H$ production modes respectively. In particular, studying the decay of a Higgs boson into muons, charm or strange quarks can give information on the Yukawa couplings to second-generation fermions. In this regard, the $H \rightarrow s\bar{s}$ channel is not a viable option, since in addition to a very low branching ratio ($\sim 0.02\%$ [38]) this decay would lead to light jets that are impossible to discriminate from the QCD background. The $H \rightarrow c\bar{c}$ channel provides a higher branching ratio ($\sim 3\%$), but still a very

Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow \gamma\gamma$	2.27×10^{-3}	$\pm 2.1\%$
$H \rightarrow ZZ^*$	2.62×10^{-2}	$\pm 1.5\%$
$H \rightarrow W^+W^{*-}$	2.14×10^{-1}	$\pm 1.5\%$
$H \rightarrow \tau^+\tau^-$	6.27×10^{-2}	$\pm 1.6\%$
$H \rightarrow b\bar{b}$	5.82×10^{-1}	$+1.2\%$ -1.3%
$H \rightarrow c\bar{c}$	2.89×10^{-2}	$+5.5\%$ -2.0%
$H \rightarrow Z\gamma$	1.53×10^{-3}	$\pm 5.8\%$
$H \rightarrow \mu^+\mu^-$	2.18×10^{-4}	$\pm 1.7\%$

Table 1.3: The branching ratios for a Standard Model Higgs boson with mass $m_H \sim 125$ GeV, together with their relative uncertainties, estimated as the ratio of the absolute uncertainty to the reported value, and accounting for the missing higher order corrections in the theoretical calculations and the errors in the SM input parameters involved in the decay [39].

challenging final state due to the c-jets, which require special jet-tagging techniques to be properly identified. Detailed algorithms are being developed, but the current amount of data is still largely insufficient to reach the sensitivity needed in order to observe such decay.

Therefore, the only feasible candidate that is accessible with the present experimental data is $H \rightarrow \mu^+\mu^-$. Despite having a tiny branching ratio ($\sim 0.02\%$), it exhibits a very clean final state that consists of two isolated muons with opposite charge, which are easily detectable and identifiable. It allows to investigate for the first time a coupling of the Higgs boson that has never been tested before, and it represents the focus of this thesis.

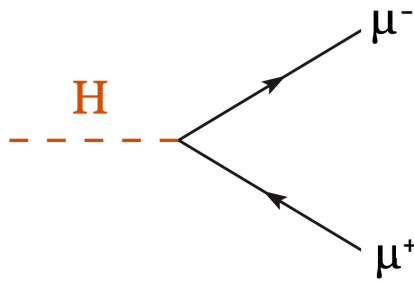


Figure 1.6: Feynman diagram showing the $H \rightarrow \mu^+\mu^-$ vertex.

THE LHC AND THE ATLAS DETECTOR

Experiments always complement the theory, providing data that can be used to validate or disprove a model, or that can be of input for new theoretical developments. In particular, measurements of the Higgs boson's properties are an essential tool in testing the predictions of the Standard Model and looking for answers to many of the open questions in particle physics.

The LHC is the most powerful particle collider in the world, and represents the best available machine to perform such measurements, together with the various experiments that collect and analyse the collision data that it provides. Among them, the ATLAS collaboration employs a general-purpose detector, designed to investigate a wide range of physics phenomena.

This chapter describes in detail the CERN accelerator complex, which includes the Large Hadron Collider and the ATLAS detector, and constitutes the experimental setup used to perform the $H \rightarrow \mu^+ \mu^-$ search presented in this thesis.

2.1 THE CERN ACCELERATOR COMPLEX

The European Organisation for Nuclear Research (*Conseil Européen pour la Recherche Nucléaire* - CERN) is an international institution that leads frontier scientific research. It operates the largest particle physics facility in the world, which hosts an accelerator complex located in an underground laboratory beneath the Swiss-French border, and a series of distinct detectors.

The CERN accelerator complex, schematically outlined in figure 2.1, consists of a chain of particle accelerators that are able to steer proton or heavy-ion beams, progressively increasing their energy. Detectors are installed around the nominal collision points where two rotating beams meet head-on, or where a beam collides against a fixed target. This way, the collision products can be collected and delivered to the experiments to be studied.

Protons are produced by stripping hydrogen atoms from their electrons by means of an electric field. They are then injected into the linear accelerator LINAC 2, that increases their energy up to 50 MeV and directs them into the Proton

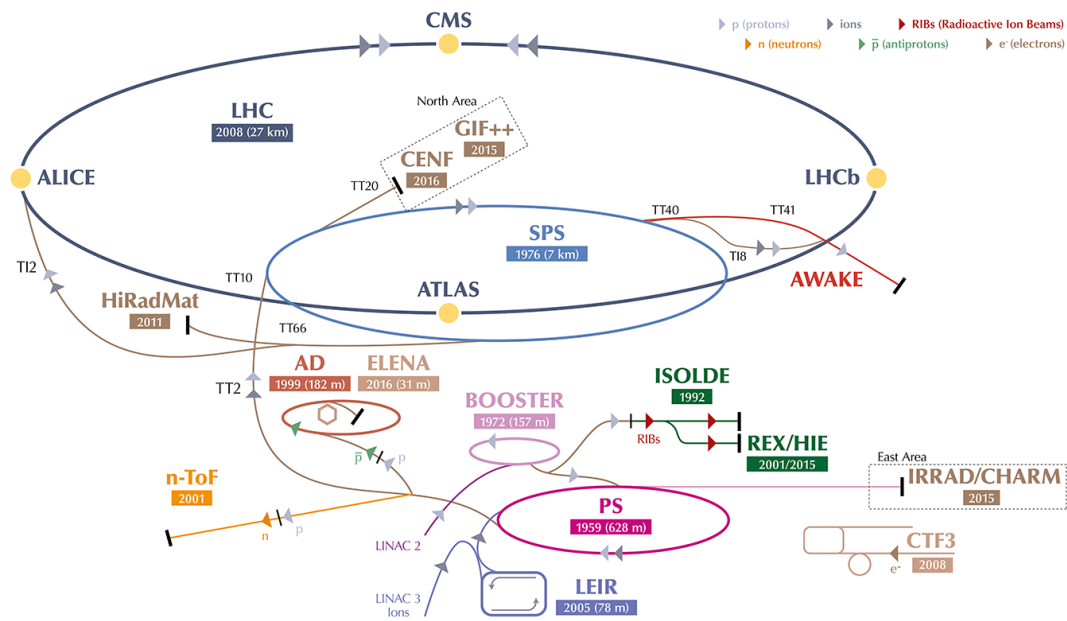


Figure 2.1: Outline of the CERN accelerator complex. Adapted from [40].

Synchrotron Booster (PSB or BOOSTER). Rotating inside the PSB the protons are further accelerated to 1.4 GeV and then enter the Proton Synchrotron (PS), where they circulate until they reach an energy of 25 GeV. The PS makes use of radiofrequency cavities to clump the continuous proton beams in bunches, spaced 25 ns in time from each other. The obtained bunches enter the Super Proton Synchrotron (SPS), where they are accelerated to 450 GeV. Afterwards, they are injected into the beam pipes of the LHC, where they rotate in two opposite directions.

Lead ions originate from a source of vaporized lead and are delivered to the LINAC 3. Then they are accelerated inside of the Low Energy Ion Ring (LEIR), and follow the same route to maximum energy as the protons. Additionally, beams of particles such as neutrons, antiprotons, electrons and other heavy-ions can be produced to feed various facilities.

2.1.1 The Large Hadron Collider

The LHC [41] is a superconducting synchrotron collider located in a 26.7 km tunnel lying 45 – 170 m underground. The tunnel consists of eight arcs and eight straight sections that form an approximate circular path, where superconducting radiofrequency cavities and different combinations of magnets are employed to respectively accelerate, focus, bend and stabilise the particle beams.

The radiofrequency cavities use an oscillating electromagnetic field with a frequency of 400 MHz, compatible with that of the particles' revolution inside the LHC, such that the beams experience an overall force that accelerates them and keeps them stably bunched [42].

More than 9000 superconducting electromagnets are arranged along the LHC tunnel in various configurations [43]. Dipoles produce an intense magnetic field of up to 8.3 T that is used to bend the particle beams keeping them on course in a semi-circular trajectory, as well as to bring them together at each interaction point and separating them afterwards. Pairs of quadrupole magnets are responsible for maintaining collimated beams, by focusing them in the vertical and horizontal plane alternatively. This counteracts the natural dispersion that would happen due to the repulsive effect of identically charged particles within the bunches. Quadrupoles are also found in triplets placed on both sides of each collision point with the goal of further tightening the beams just prior to a beam crossing, in order to maximise the number of interactions [44]. In addition sextupole, octupole and decapole magnets are also employed to correct for small imperfections in the magnetic fields of the dipoles, and to improve the beam quality by compensating for secondary effects such as the electromagnetic interactions among bunches [45].

When the two counter-rotating beams reach the design energy, they are brought together in four collision points along the tunnel, in correspondence of the four main LHC particle detectors: ALICE, ATLAS, CMS and LHCb. ATLAS and CMS [46] are both general-purpose detectors aiming at recording a wide range of physics processes. ALICE and LHCb, on the other hand, have more specific goals: ALICE [47] is a heavy-ion detector designed to study the physics of strongly interacting matter at extreme energy densities, while LHCb [48] focuses on investigating particles that contain the b quark to measure CP violation. There are also four smaller experiments that make use of the high-energy collisions produced at the LHC: FASER, LHCf, MoEDAL and TOTEM. FASER [49] has recently been installed roughly 480 m east of the ATLAS detector, where it looks for exotic weakly interacting particles, while MoEDAL [50] is located around the LHCb interaction point and is specialised in the search for magnetic monopoles or other massive charged particles, which are predicted by a large number of theories beyond the Standard Model. Finally, TOTEM [51] and LHCf [52] study physics processes in the region very close to the beam line, using detectors located on either side of the CMS and ATLAS interaction points respectively.

The timeline of the main LHC research program is shown in figure 2.2. It is organised in runs, which are periods of mostly continuous operation during which the machine parameters are kept almost constant. Within one run approximately seven months of $p - p$ collisions are delivered, followed by one month of lead-lead collisions. Afterwards, the LHC is turned off for a time frame referred to as a long shutdown, when a series of refurbishments and improvements that involve the whole CERN facility take place, to prepare the machines for the next run. After its first collisions in 2011, the LHC completed two runs, Run 1 and Run 2, and is currently undergoing its second long shutdown (LS2). The LS2, together with the third long shutdown (LS3) that will follow Run 3, aims at increasing the performance of the accelerator and of the detectors for the long-term future, towards the ultimate experimental stage called high-luminosity LHC (HL-LHC) [53].



Figure 2.2: Timeline of the past and foreseen runs and shutdowns of the Large Hadron Collider. In blue the LHC runs and shutdowns, and in red the future HL-LHC.

2.1.2 Collider parameters

The performance of a particle collider is usually quantified in terms of two key parameters: the centre-of-mass energy and the luminosity.

The centre-of-mass energy $\sqrt{s}$ is the energy available when two particles collide. It determines the suitable final states of a collision and is used as a measure of the reachable mass range of an experiment, since conservation laws require that $\sqrt{s}$ is at least equal to the total mass of the produced particles. At the LHC, the centre-of-mass energy increases proportionally to the energy E_p of the colliding protons, and can be written as $\sqrt{s} = 2E_p$. During Run 2, when 6.5 TeV protons circulated in the beam pipes, the centre-of-mass energy was $\sqrt{s} = 13$ TeV, compared to the maximum of 8 TeV reached during Run 1.

The luminosity, instantaneous or integrated, is a figure of merit used to quantify the potential interactions that can happen at a collider. The event rate for a certain physics process K originating after a collision can be expressed as the product of its cross section σ_K and the instantaneous luminosity L :

$$\frac{dN_K}{dt} = \sigma_K \times L. \quad (2.1)$$

The cross section is specific of the interaction type and usually depends on $\sqrt{s}$ while the instantaneous luminosity, which indicates the expected rate of interactions among the beam particles, depends only on the characteristics of the accelerator. In order to maximise the probability of collisions of interest, it is crucial to optimise the machine such that L is large.

The instantaneous luminosity decreases with time, following the continuous beam depletion caused by particle collisions and dispersions that happen at the LHC. In fact, considering n_b bunches per beam and N_p particles per bunch, and assuming that the particles within a beam are Gaussian distributed [54], L can be approximated as

$$L = \frac{N_p^2 n_b f_{\text{rev}} \gamma_p}{4\pi \varepsilon_{xy} \beta^*} \mathcal{F}, \quad (2.2)$$

where the product of the transverse geometric emittance ε_{xy} and the betatron function at the interaction point β^* measure the beam size¹, f_{rev} is the LHC revolution frequency, π is the Archimede's constant and γ_p is the relativistic

¹ The geometric transverse emittance ε_{xy} represents the average transverse size of a particle beam, and the betatron function β describes its modulation resulting from the motion through the focusing

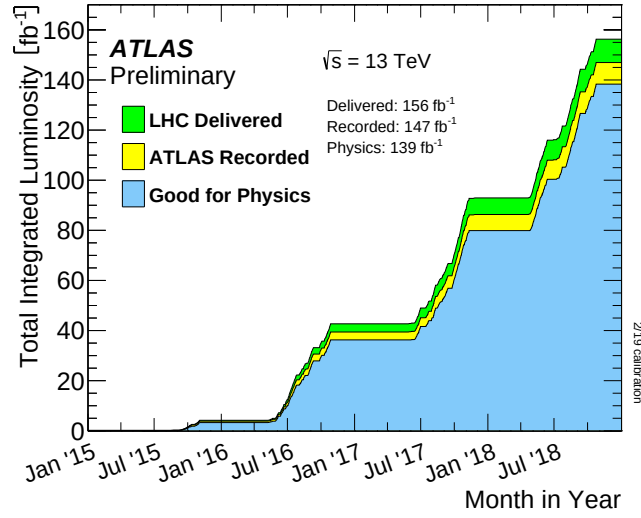


Figure 2.3: Run 2 integrated luminosities delivered by the LHC, recorded by the ATLAS detector and available for physics analyses [55].

Lorentz factor of the protons. Lastly, $\mathcal{F}$ is a geometric reduction factor that takes into account the crossing angle between the beams, the beam size and the length of the bunches.

The integrated luminosity is the integral of L over time, $\mathcal{L} = \int L dt$. It is measured in inverse femtobarn (fb^{-1}) units, and defines the expected number of particle interactions per target cross section in a given time interval. Therefore, it is used to quantify the amount of data delivered by a collider. However, detectors are not perfectly efficient and thus a small fraction of the delivered data will not be recorded. Moreover, part of the recorded events is not sufficiently qualified to be used for physics analyses due to suboptimal detecting conditions. The so-called GOODRUNLIST (GRL) keeps track of all the luminosity intervals in which the detector operated as intended, and datasets are required to be included in its catalogue in order to reject pathological collisions. Figure 2.3 shows the Run 2 integrated luminosities. During this time, the LHC delivered a total of 156 fb^{-1} and ATLAS recorded 147 fb^{-1} , of which 139 fb^{-1} were suitable for physics analyses.

High values of the instantaneous luminosity not only increase the probability of a hard scattering, but also that of the more abundant softer collisions that happen concurrently, referred to as the in-time pile-up. Collectively, the term pile-up indicates the average number of $p - p$ collisions per bunch crossing that happen in addition to the collision of interest. The in-time pile-up is the main component of this background, but other contributions come from secondary effects. Among these, the out-of-time pile-up consists of remnants of the bunch crossings preceding the collision of interest and also includes the contribution of residual neutrons and photons in the surroundings of the detectors or in the beam pipes.

magnets. The product $\sqrt{\beta^* \epsilon_{xy}}$ gives the beam size at the crossing point, measured perpendicularly to the beam's direction of motion.

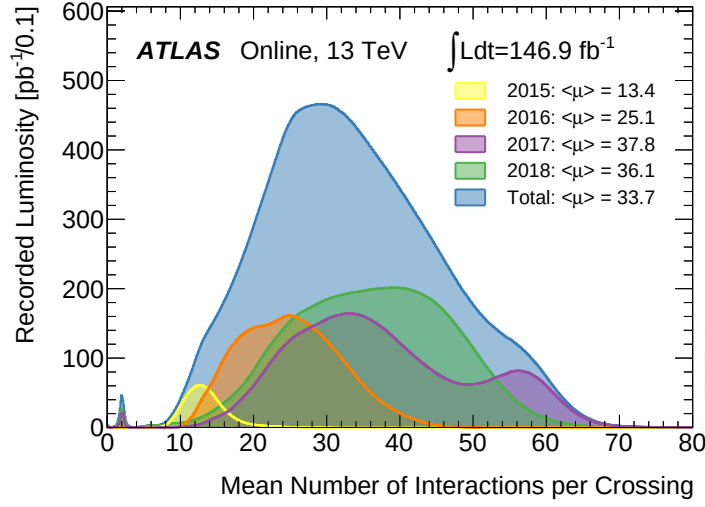


Figure 2.4: Pile up profile for $p - p$ collisions delivered to the ATLAS detector during Run 2 of the LHC [55].

Understanding and modelling the pile-up is crucial, as a large number of concurrent interactions pose a major challenge to both the sensors and to the physics analyses, which must be able to record and identify the particles coming from the collision of interest within high background levels. At the LHC the in-time pile-up follows a Poisson distribution with mean value

$$\mu_{\text{pu}} = \frac{L \sigma_{\text{inel}}}{f_{\text{rev}} n_b}, \quad (2.3)$$

where σ_{inel} is the total cross section for inelastic scatterings. It can be measured using the so-called minimum-bias events, which are events recorded according to very loose detection criteria in order to minimise the potential bias that these criteria introduce. The Poisson mean value is different for different bunches, and decreases in time with the instantaneous luminosity. Its average taken over time, $\langle \mu_{\text{pu}} \rangle$, is commonly used to quantify the pile-up during a run. As shown in figure 2.4, the value of $\langle \mu_{\text{pu}} \rangle$ during the entire Run 2 was 33.7.

The foreseen HL-LHC will deliver an unprecedented amount of 14 TeV collision data, corresponding to peak luminosities of $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ or higher and to integrated luminosities up to 4000 fb^{-1} over several runs. These conditions require not only a series of improvements in many components of the accelerator complex, but also major upgrades in the detectors, which must be able to withstand pile-up levels of the order of $\langle \mu_{\text{pu}} \rangle = 200$. Overall, the proper study of HL-LHC collisions will make it possible to detect rare events never witnessed before, and to push the understanding of the energy frontier.

2.2 THE ATLAS DETECTOR

The ATLAS detector [57] is located along the LHC ring, where it records the particles produced in $p - p$ or heavy-ion collisions. The collected data events are used to reconstruct the original interactions, to test the Standard Model's predictions and explore potential new physics scenarios. To achieve this, ATLAS makes use of a design rich of fast and high-resolution sensors that cover a solid angle of almost 4π around the collision point, and that allow the detection of as much useful events as possible.

ATLAS is the largest collider detector ever built, being 25 m high and 44 m long and having an approximate weight of 7000 t. As shown in figure 2.5, it has a cylindrical structure that develops in concentric layers around the beam line, and is symmetric in the forward and backward direction. It is composed of three main detector subsystems, each one with a specialised purpose: the inner detector to track charged particles, the calorimeter system to measure particle energies and the muon spectrometer to identify and measure muons. The setup is complemented by a superconducting magnet system that consists of one solenoid and three toroid magnets, which bend the trajectories of the charged particles proportionally to their charge and momenta, aiding measurements of these quantities [58]. The solenoid surrounds the inner detector and provides a uniform field of around 2 T mostly parallel to the beam line, while the toroids provide the muon spectrometer with an azimuthal field with inhomogeneous intensity of up to 0.5 T in the central region and 1.0 T in the forward regions. As a result, the bending occurs mainly in the plane orthogonal to the beam line within the solenoid, and along the beam line within the toroids, with almost no bending in the transition space between the two types of magnets.

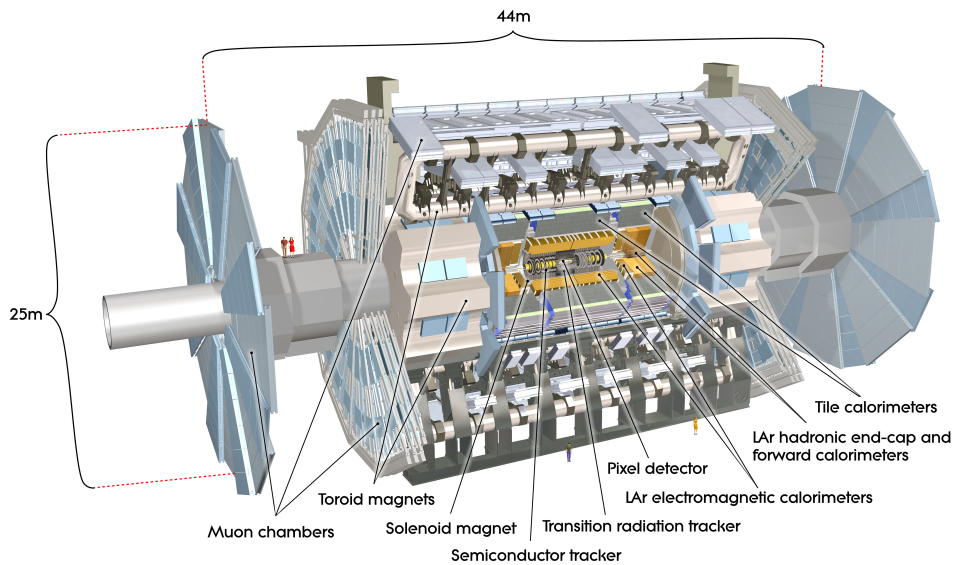


Figure 2.5: Computer-generated view of the ATLAS detector [56].

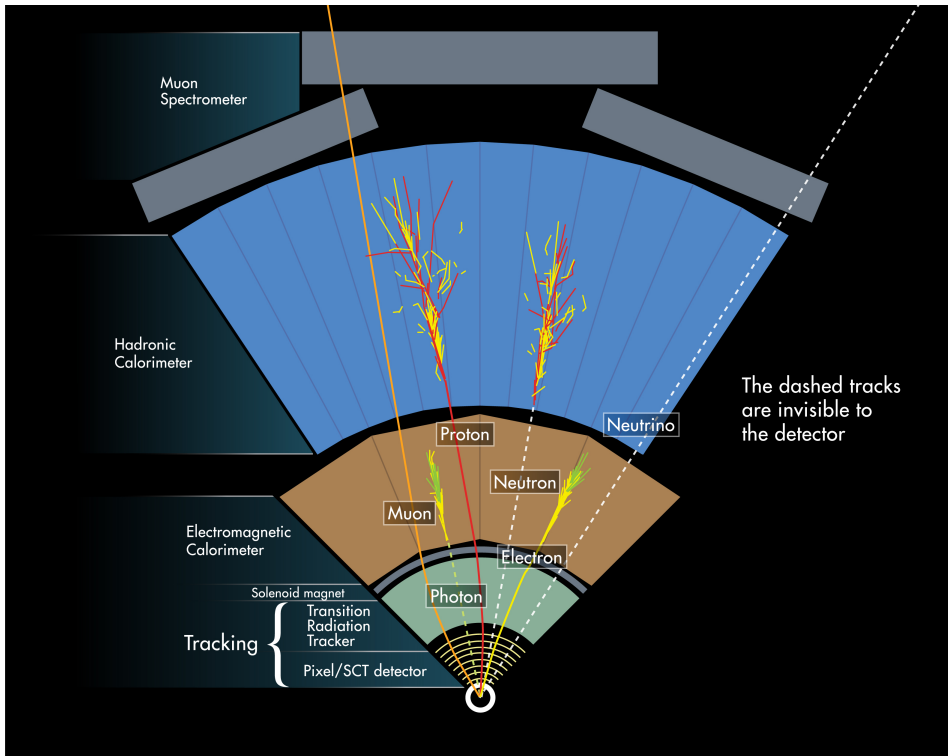


Figure 2.6: Diagram of particle paths in the ATLAS detector [59].

The ATLAS subsystems work together to identify, track and measure the energies and momenta of most of the particles that traverse them. As shown in figure 2.6, different types of particles interact differently with the various detectors while they move away from the point where the collision of interest took place, called primary vertex. First, the collision products are met by the inner tracker. If these particles are charged, they interact with its materials producing electrical signals along their trajectory, which is bent by the solenoidal magnetic field. Escaping the tracker, the particles traverse the calorimeters, where they deposit their energy in a way that varies with the particle type. Most particles are stopped by the calorimeters, with the exception of neutrinos, which lack both electric and strong charge and are therefore invisible to ATLAS, and muons, which at the typical LHC energies have only minimal interactions and are able to pass through the calorimeters almost undisturbed. Muon trajectories are then bent by the toroidal magnetic fields and detected by the spectrometer. Short-lived particles can also be generated in a collision. They travel a measurable distance from the primary vertex and then decay, producing a displaced secondary vertex that corresponds to the position where the decay took place.

2.2.1 Coordinate system and kinematics

The ATLAS experiment adopts a coordinate system that, as shown in figure 2.7, is specifically chosen to suit the detector design. The origin is located at the nominal

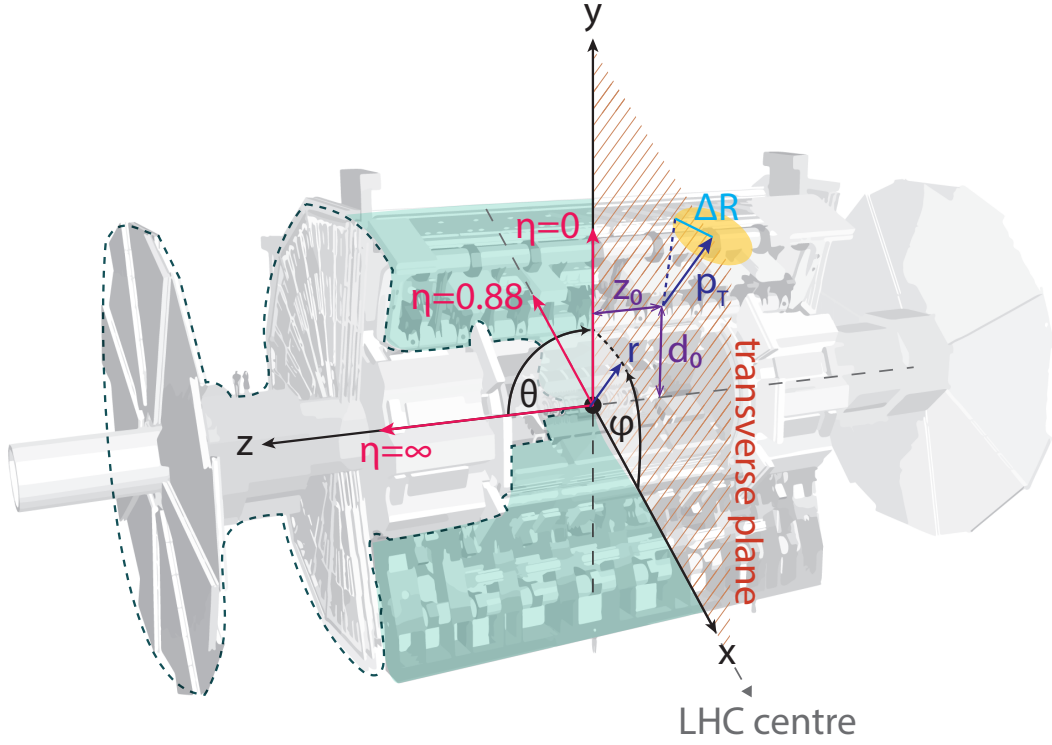


Figure 2.7: Coordinate systems and main kinematic variables used in ATLAS. The magenta arrows show three different pseudorapidity values, and the dashed orange area corresponds to the transverse plane. The region highlighted in cyan shows half of the barrel, and the region within the dashed blue line is one endcap. The p_T of a track is shown in blue, surrounded by the yellow cone base that defines the angular distance ΔR . The impact parameters are indicated by the purple solid lines.

collision point, which coincides with the center of the detector. The coordinate system is right-handed, with the Cartesian z -axis aligned with the direction of the counter-clockwise rotating beam, the positive y -axis pointing vertically upwards, and the x -axis pointing radially inwards towards the centre of the LHC ring. The $x - y$ plane is called transverse plane, and thanks to the hard scattering topology is the plane where most of the quantities of interest are reconstructed. The most used variables in this context, indicated with the subscript T, are the transverse momentum p_T and the missing transverse momentum $\cancel{p}_T$, where the latter is estimated from the total transverse momentum conservation and gives information on particles that traversed the detector without generating a signal. Two additional important quantities are commonly used to describe the proximity of a particle to the primary vertex, expectedly located at the origin: the transverse impact parameter d_0 is the shortest distance between a track and the beam line in the transverse plane, and the longitudinal impact parameter z_0 identifies the distance in z between the primary vertex and the point on the track used to evaluate d_0 .

Given the symmetry of the ATLAS detector, which follows that of the expected collision products, spherical and cylindrical coordinates are also often used. The

radial coordinate that indicates the distance from the origin is denoted by r , the azimuthal angle φ is measured from the positive x -axis in the $x - y$ plane, and the polar angle θ relative to the beam axis is measured from the positive z -axis.

An additional variable called rapidity can be used to quantify the position of a particle with respect to the transverse plane, and is defined as

$$y = \ln \sqrt{\frac{E + p_z}{E - p_z}}, \quad (2.4)$$

where E is the energy of the particle and p_z is the momentum component along the beam axis. Differences Δy are invariant under Lorentz boosts in the z -direction, and thus the rapidity is particularly useful in situations where, due to the composite nature of the protons, the centre-of-mass of a collision does not coincide with the detector's rest frame, leading to particles boosted along the beam line.

In the ultrarelativistic limit y converges to the pseudorapidity

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (2.5)$$

which has the same invariance properties but is much easier to calculate, because it does not require measuring quantities along the z -direction, where the flux of particles is more intense. When $\eta = 0$ a particle is directed transversally with respect to the beam axis, and when $\eta \rightarrow \pm\infty$ a particle moves close to the beam axis in the so-called forward regions.

In terms of pseudorapidity, the ATLAS detector can be divided into three sections: a barrel, which is cylindrically symmetric and occupies the central region characterised by $|\eta| < 1.4$, and two identical circular regions called endcaps that are located on each side of the barrel, covering the range $1.5 < |\eta| < 5$. The pseudorapidity can also be used to measure the distance between the trajectories of different particles, which is given in terms of their angular separation

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}, \quad (2.6)$$

and is related to the components of the vector momentum $\mathbf{p}$ through the formulae

$$\tanh \eta = \frac{p_z}{|\mathbf{p}|} \quad \cosh \eta = \frac{|\mathbf{p}|}{p_T}, \quad (2.7)$$

where the magnitude of the transverse momentum can be written as

$$p_T = \sqrt{p_x^2 + p_y^2} = p \sin \theta \quad (2.8)$$

using the momentum component along the x -axis p_x and the momentum component along the y -axis p_y .

2.2.2 Tracking system

The inner detector (ID) [60] is the innermost subsystem of ATLAS and is closest to the nominal collision point, covering the pseudorapidity region $|\eta| < 2.47$. For this reason, it must be able to tolerate high doses of radiation. Its goal is to determine precisely the trajectories and momenta of the charged particles that traverse it, and to estimate the position of the interaction vertices. This is accomplished using very low material densities to leave the particles as unaltered as possible, such that they can proceed along their path towards the following subsystems.

As shown in figure 2.8, the ID consists of four components relying on different kinds of gaseous and semiconductor sensors and arranged concentrically from the collision point outwards: the insertable b-layer (IBL), the pixel detector (Pixels), the semiconductor tracker (SCT) and the transition radiation tracker (TRT).

A charged particle interacts with the sensors by ionisation, producing electrical signals that are recorded as hits, and that can be combined to reconstruct the track that describes the particle trajectory, curved in the xy plane by the solenoidal field.

INSERTABLE b-LAYER

The IBL is placed in the barrel region, and it is the detector that is closest to the collision point. It was installed during the first long shutdown (LS1) between Run 1 and Run 2. It has very high granularity, in order to withstand the extreme radiation levels that affect its location, and has the purpose of providing a very precise measurement of primary and displaced secondary vertices. It consists of 12 million silicon pixel sensors arranged in a cylindrical structure that covers the full 4π angle around the beam line. Each sensor has a size of $50 \times 250 \mu\text{m}^2$, and is only 33.25 mm distant from z -axis. The hit resolution of this setup, in the transverse and longitudinal direction, is $8.5 \mu\text{m}$ and $47 \mu\text{m}$ respectively.

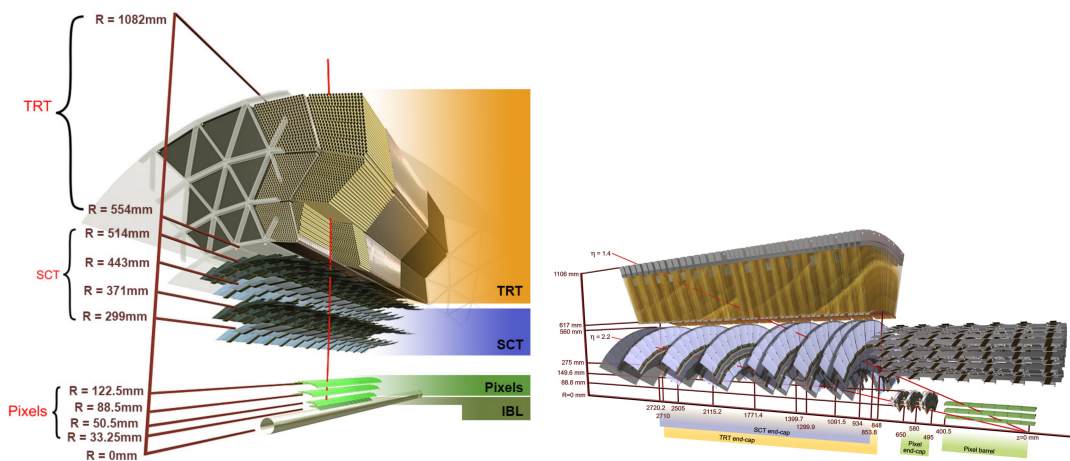


Figure 2.8: Schematic view of the ATLAS inner detector system in the barrel (left) and in the endcaps (right) [61, 62].

PIXEL DETECTOR

The pixel detector consists of modules of $50 \times 400 \text{ } \mu\text{m}^2$ silicon pixel sensors, arranged in three concentric cylindrical layers in the barrel, and three disks in each endcap region. Overall, the area corresponding to $|\eta| < 2.5$ is covered hermetically, such that a traversing particle is expected to leave hits in each layer. Both in the barrel and in the endcaps, the intrinsic accuracy of the system in the transverse and longitudinal direction is $10 \text{ } \mu\text{m}$ and $115 \text{ } \mu\text{m}$ respectively.

SEMICONDUCTOR TRACKER

The SCT is located further away along the beam line, and relies on the less granular silicon micro-strip detectors. The sensors are grouped in modules organised in four layers in the barrel, and nine disks in each endcap. Each module consists of two planes of sensors arranged in an alternating orientation to provide two-dimensional measurements of the coordinates. The resulting intrinsic transverse and longitudinal accuracies are $17 \text{ } \mu\text{m}$ and $580 \text{ } \mu\text{m}$ respectively.

TRANSITION RADIATION TRACKER

The TRT is the outermost component of the inner detector. It uses layers of cylindrical straw drift tubes with a diameter of 4 mm , filled with a mixture of xenon (70%), carbon dioxide (27%) and oxygen (3%) gas. They are able to record the passage of a particle when ionised, providing an intrinsic spatial resolution of $130 \text{ } \mu\text{m}$. The tubes are 144 cm long and parallel to the beam direction in the barrel, and 37 cm long in the radial direction in the endcaps. Their layers are interleaved with a radiator medium, with which the charged particles interact by emitting transition radiation, with an intensity proportional to their mass. Measuring this radiation allows to perform particle identification.

2.2.3 *Calorimeter system*

The calorimeter system [63, 64] of ATLAS, schematically depicted in figure 2.9, surrounds the tracker and measures the energy of the traversing particles.

It consists of alternating layers of high-density absorbing material and detecting, or active, material. The incoming particles interact with the absorbing material and initiate a cascade, or shower, of secondary particles with decreasing energy, which are detected by the active layers. If the showers are completely contained within the calorimeter, their intensity and structure can be used to determine the energy and type of the particles that generated them.

Electrons and photons induce electromagnetic showers, which consist of ulterior particles of the same type mostly generated via bremsstrahlung and e^+e^- pair production. Hadrons, on the other hand, produce hadronic showers as they interact with the atomic nuclei of the absorber. These showers can contain a large number of different particles, some of which can give rise to secondary electromagnetic showers.

A measure of the longitudinal shower development is given by the radiation length in the electromagnetic case, defined as the distance over which the energy

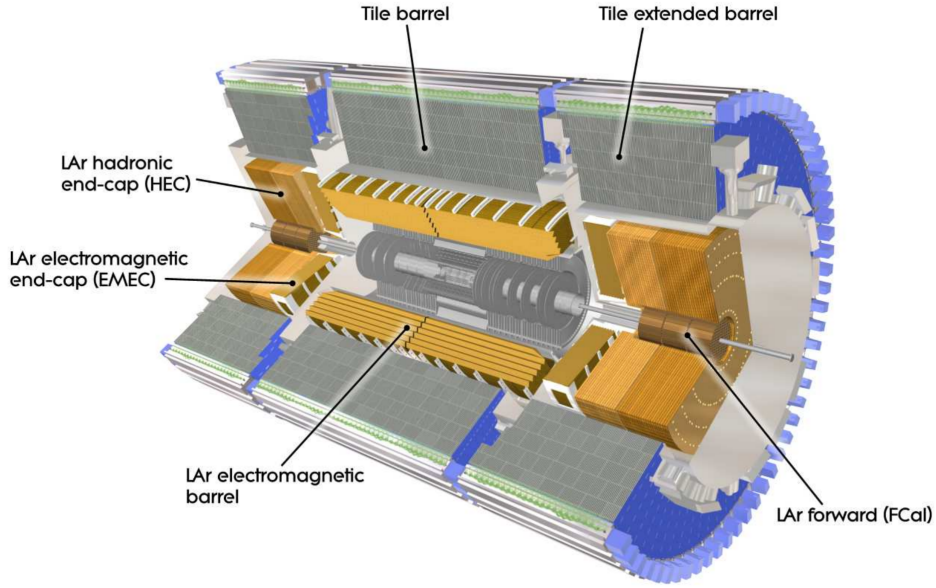


Figure 2.9: Schematic view of the ATLAS calorimeter system [62].

is reduced by one Euler number $e = 2.71828$, and by the interaction length for hadronic showers, defined as the mean distance after which a hadron undergoes an inelastic nuclear interaction. Electromagnetic showers typically develop faster, while hadronic showers exhibit a much larger longitudinal structure and require more material to be absorbed.

To exploit these characteristics, the calorimeter system consists of two distinct components: the electromagnetic calorimeter (EMCal) that aims at detecting electromagnetic showers, and the hadronic calorimeter (HCal) that measures hadronic showers. The total acceptance of the system is $|\eta| < 4.9$.

ELECTROMAGNETIC CALORIMETER

The EMCal is situated right outside the tracker. It is a high-granularity system that comprises a barrel component, which covers the region $|\eta| < 1.475$, and two endcaps at $1.375 < |\eta| < 3.2$. The active material used is liquid argon, which guarantees a fast response and is radiation resistant, while the absorber consists of lead plates symmetrically positioned around φ . These materials are arranged in three sampling layers of decreasing granularity.

An additional thin layer of argon, called presampler, is installed on the inner surface of the EMCal, covering the region $|\eta| < 1.8$. Its purpose is to account for the energy lost due to showers produced in the innermost regions of the detector.

Overall, the EMCal is approximately 22 radiation lengths and 1.5 interaction lengths thick, which suffices to fully contain electromagnetic showers of most energies.

HADRONIC CALORIMETER

The hadronic calorimeters are organised in three separate subsystems, for a total

thickness of 10 interaction lengths: the tile calorimeter (TileCal) in the barrel region, the liquid argon endcap calorimeter (HEC) and the liquid argon forward calorimeter (FCal).

The modules composing the TileCal use plastic scintillating tiles as active material and steel plates as the absorber, and are arranged in three layers of different thickness and granularity, split in a barrel region $|\eta| < 1.0$ and an extended barrel region $0.8 < |\eta| < 1.7$.

The HEC consists of two wheels located on each endcap, covering the region $1.5 < |\eta| < 3.2$. Its detectors are organised in four layers of granularity varying with η , which use copper plates as absorber material and liquid argon as active material.

The FCal is installed in the very forward endcap region of ATLAS, $3.1 < |\eta| < 4.9$, where it aims at measuring the activity that is not detectable by the other calorimeters. To achieve this, its structure is composed of three modules for each endcap. The innermost module uses copper to initiate electromagnetic showers, while the other two use tungsten. The active material is, in both cases, liquid argon.

2.2.4 Muon system

The muon spectrometer (MS) [65] is the outermost subsystem of ATLAS, and takes care of the particles that escaped undetected from the entire calorimeter system. Apart from muons, a tiny fraction of them consists of hadronic shower remnants, referred to as the punch-through.

The spectrometer has three main purposes: muon identification, muon momentum measurement and muon triggering. To achieve these goals, it employs two distinct types of chambers, the tracking chambers and the trigger chambers, consisting of assemblies of different kinds of gaseous detectors. Muons ionise the detecting gas medium, producing electrical signals that can be collected to retrieve the particle positions along their trajectories, which are curved in the rz plane by the toroidal magnetic fields.

The design of the muon spectrometer, as shown in figure 2.10, consists of three barrel layers referred to as the inner, middle and outer layer based on their radial distance from the beam line, and three muon stations for each endcap similarly referred to as the inner, middle and outer station according to their distance from the collision point along the beamline. Each outer station consists of a fixed wheel with a diameter of approximately 20 m, or outer wheel, and each inner station consists of a wheel of 9.3 m diameter, or small wheel. Lastly, each middle station comprises four so-called big wheels with a diameter of 25 m. Every barrel layer and endcap station is instrumented with a combination of tracking and triggering chambers.

TRACKING CHAMBERS

The tracking chambers provide high-precision measurements of the muon trajectories, with a coverage up to $|\eta| < 2.7$. They employ two different technologies: the cathode strip chambers (CSCs), which are multi-wire proportional chambers, and the monitored drift tubes (MDTs), whose detecting medium is a mixture of

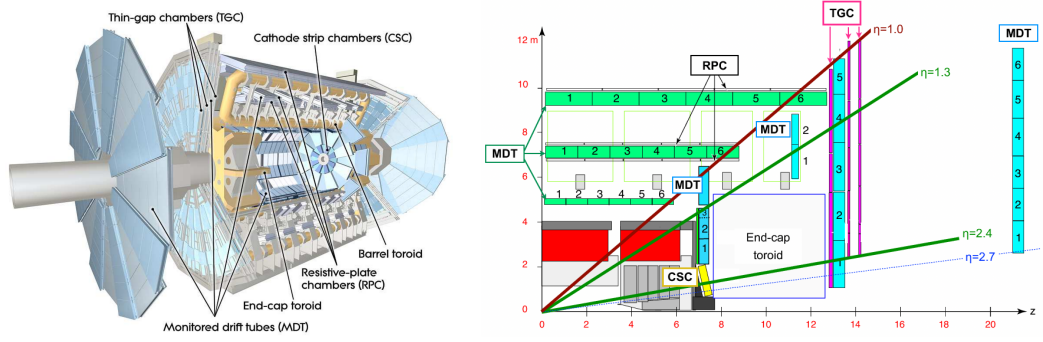


Figure 2.10: Cutaway view of the ATLAS muon system (left) [62] and schematic representation of a quarter-section of the muon system (right) [66].

argon and carbon dioxide. The MDTs are arranged in series of multiple stacked tubes, and distributed in all the barrel layers and endcap stations, and have a space resolution of about $40 \mu\text{m}$. The $|\eta| > 2$ region of the innermost endcap station, where the flux of incoming particles is more intense, is instrumented with CSCs, which are faster and more resistant to radiation damage, and are therefore able to provide reliable measurements in more difficult conditions.

TRIGGER CHAMBERS

The trigger chambers use fast sensors, with time resolution of the order of 1 ns. Their goal is to detect the passage of a muon within the very limited time frame needed to select or reject an event during a bunch crossing, according to a decisional procedure called triggering, which will be further discussed in section 2.2.5. Additionally, they contribute to the measurement of the muon trajectories in the direction orthogonal to that of the tracking chambers. Resistive plate chambers (RPCs) are used in the $|\eta| < 1.05$ barrel region, while multi-wire proportional chambers called thin gap chambers (TGCs) are installed in the two innermost endcap stations, covering $1.05 < |\eta| < 2.7$.

2.2.4.1 Outlook on the muon system

The unprecedented peaks of instantaneous luminosity foreseen after LS2 provide more data and open many new physics opportunities, but at the same time come with increased pile-up levels that pose major challenges to the detectors, to the data storage and to the offline analysis infrastructure of the experiments.

Despite the higher particle flux, the trigger system will be required to perform an efficient online selection that maintains the event rates at a level that is manageable by the read-out systems. Moreover, the tracking sensors will need to have a fast response and a high resolution that allow to isolate tracks in an extremely crowded environment. Finally, all the sensors must be strongly radiation-hard, especially in the forward regions where the flux of incoming particles from $p - p$ collisions is more intense.

The ATLAS collaboration has planned a series of upgrades aiming at addressing these issues, preparing the detector and the analysis software for the next rounds of

data taking [67,68]. One of these upgrades consists of removing the two innermost endcap stations of the muon spectrometer, the small wheels, and replacing them with the two so-called new small wheels (NSW), of similar size but improved capabilities.

In fact in the endcap region, and in particular in correspondence of the small wheels, the particle rate expected after the shutdown will exceed the operational capabilities of the current tracking and trigger chambers, which are suitable only up to luminosities of $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. As a result, both the muon trigger efficiency and the tracking performance will be compromised.

A degradation of the tracking is expected because the small wheels are the only stations to provide information in front of the toroid magnet, which is crucial to determine the muon momentum accurately by exploiting the curvature in the magnetic field. Without this, muons with transverse momenta larger than 100 GeV will be highly affected, since their measurement depends mostly on the muon spectrometer and less on the inner detector, and up to 70% of the signals coming from highly energetic particles can be lost.

Concerning the endcap trigger, the Run 2 algorithms select incoming particles that they identify as muons when their trajectory, measured by the middle muon station, can be loosely matched to the nominal collision point. Additional coincidences with the TGC sensors in the inner station, and with the TileCal in the region $1.05 < |\eta| < 1.3$ are required, with the main goal of rejecting low energy objects generated in the toroids region [69]. However, more robust requirements must be implemented in terms of η coverage, angular resolution and granularity of the inner station chambers in order to cope with the increased luminosity after LS2, which will otherwise completely saturate the chambers and compromise the overall performance of ATLAS.

The NSW upgrade addresses both the needed trigger rates suppression and the performance of the tracking chambers by equipping the inner muon stations with a set of new precision sensors, able to work at high rates with excellent space and time resolution. These detectors complement the middle station providing additional high-quality trigger and tracking information to identify muons that originate from the collision point, and to achieve better p_T measurements. For example as shown in figure 2.11, requiring NSW trigger measurements in addition to those coming from the big wheel allows to efficiently reject objects that do not come from the primary vertex, such as low- p_T particles created in the toroidal area.

As depicted in figure 2.12, the NSW layout consists of 16 partially overlapping trapezoidal sectors of alternating smaller and larger size, arranged radially to form a disk structure. Each sector is composed of four wedges stacked in the z -direction, and each wedge contains four layers of detectors such that a muon moving in the forward direction is expected to traverse an overall set of 16 active layers.

Two different types of sensors are employed: small-strip thin gap chambers (sTGCs) are used as trigger chambers in the two external wedges, and resistive-strip micro-mesh gaseous chambers (MMs) are tracking chambers that characterise the two inner wedges. The sTGC sensors represent an improved version of the thin gas chambers already installed in the endcap wheels, and are expected to provide

a space resolution better than $100\text{ }\mu\text{m}$ with a rate capability of 30 kHz/cm^2 . The MMs are a novel detector technology at collider experiments. They rely on gas ionisation and amplification produced thanks to a thin metallic micro-mesh layer, which grants them an intrinsic space resolution of the order of $50\text{ }\mu\text{m}$ and a high rate capability.

The project required a set of detailed studies to simulate the response and integration of the NSW at high luminosity conditions, as reported in [70], and the construction and installation of the wheels, together with all the required hardware and software infrastructures, involves different institutes in various fields of expertise. The progress of the upgrade is currently within the schedule and quality required, and the effort is expected to be completed at the end of 2021 [71].

2.2.5 Trigger system

The trigger system examines the enormous amount of events produced in a bunch crossing and selects only those that qualify as relevant for physics analyses. The decisions are based on which particles are detected and on their characteristics, and use a subset of the detector information to reduce the event rate to a level

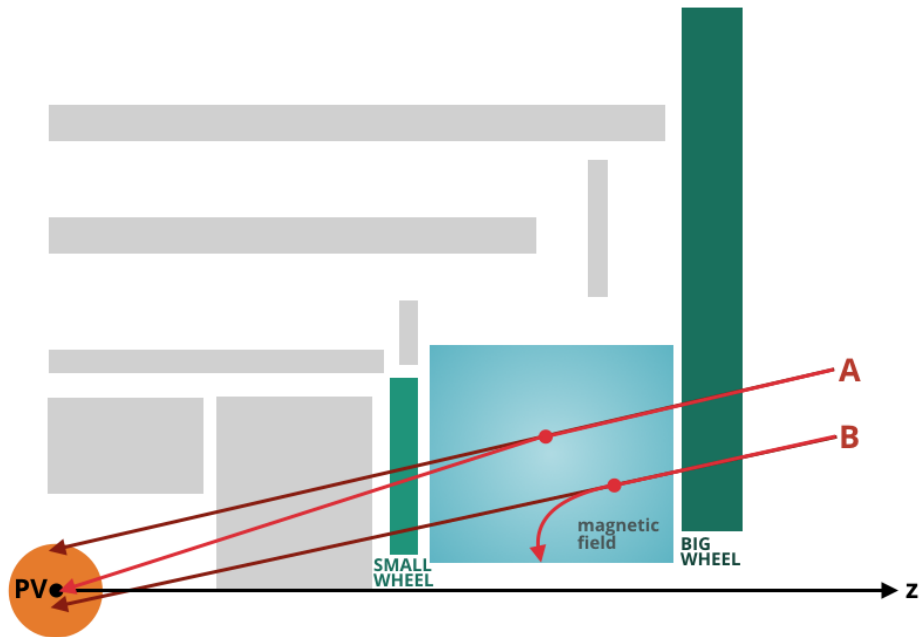


Figure 2.11: Schematic view of a quarter section of the muon system, showing in green a (new) small wheel and a big wheel. In red, two tracks extrapolated using measurements from both wheels, corresponding to a real high- p_T muon (A) and a low- p_T particle created in the toroidal area (B). In brown, the same tracks extrapolated only using the big wheel. The orange circle represents the area where tracks can be considered loosely matched to the primary vertex, and triggered as muons.

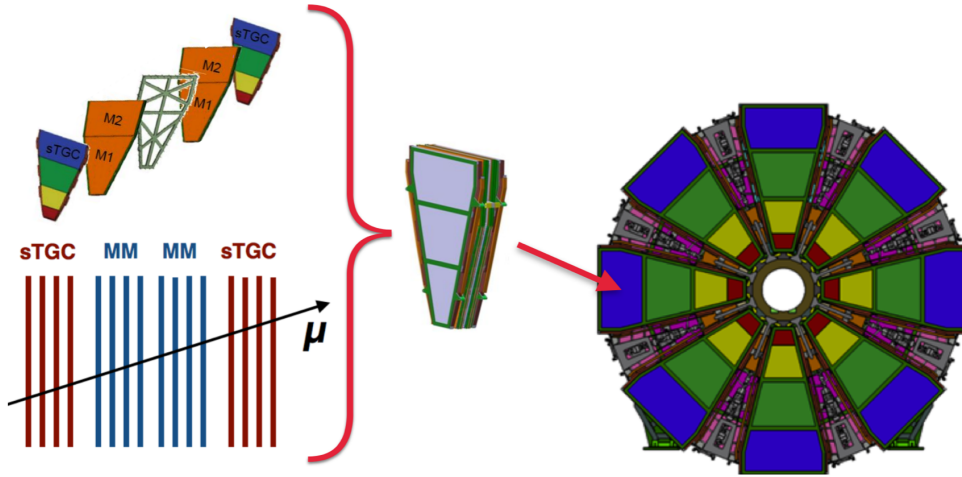


Figure 2.12: Cutaway view of the ATLAS NSW layout, adapted from [70].

manageable by the read-out and storage systems and by the offline processing farm, which have finite time and space capabilities.

ATLAS employs a trigger system that works in two stages. The Level-1 (L1) trigger [72] uses a fast hardware-based logic that is able to make decisions within 25 ns of a bunch crossing. It profits from the information collected by the calorimeters and the muon spectrometer to reduce the incoming rates from 40 MHz to about 100 kHz, selecting only those events that contain signatures associated with muons, photons, electrons, jets, τ leptons, large missing transverse momentum or large overall transverse energy. Additionally, it defines regions of interest within the detector, corresponding to the locations of the selected events.

The high-level trigger (HLT) [73] processes the regions of interest identified by the L1 triggers, using software-based techniques that are able to further reduce the event rate to approximately 1 kHz within 2.5 μ s. To achieve this, the information coming from the inner tracker is combined with that of the other subsystems to reconstruct in more detail the single physics objects and the overall topology of the events. The datasets selected this way are then finally compressed and passed to the read-out system to be permanently stored.

ATLAS provides dedicated combinations of L1 and HLT triggers, called trigger menus, each one aiming at identifying specific objects and signatures in an event. This way, a given physics analysis can use only those datasets that are relevant for the topology of the physics process under examination, and implement a more efficient workflow. At high instantaneous luminosities, trigger menus with low thresholds may be prescaled, meaning that only a fraction of the selected events is accepted. This prescaling allows to reduce the event rate for processes such as those involving the production of low-energy objects, which are very abundant and would otherwise overwhelm the data acquisition system and the storage.

2.2.6 *Forward detectors*

Three additional detector systems cover the very forward region of ATLAS [74]: LUCID, ALFA and ZDC. LUCID uses two Cherenkov detectors that lie at ± 17 m from the ATLAS collision point. The ALFA components consist of eight scintillator fibre detectors located at ± 240 m, and lastly ZDC employs two calorimeters installed at ± 140 m from the interaction point.

These detectors do not contribute directly to measuring collision products suitable for physics analyses. Instead, they collect the particles that travel further along the beam line to provide auxiliary measurements. In particular, they have the main goal of estimating the total luminosity delivered to ATLAS by the LHC and to calibrate the luminosity monitors of ATLAS, and also contribute measurements of minimum bias events.

EVENT SIMULATION AND PHYSICS OBJECTS

Running the ATLAS detector is only the starting point of the many physics analyses that can be performed with the data it collects. Its subsystems, exposed to the intense flux of LHC collision products, record the passage of traversing particles in the form of disjoint digital signals that constitute the raw data, which must then be processed by means of reconstruction and identification algorithms in order to trace back the original interacting objects.

Alongside a measurement, simulated samples also represent a critical part of any physics experiment. They emulate the LHC collisions and the response of the ATLAS detector on the basis of theoretical and structural predictions. The resulting artificial events undergo the same processing as the raw data and can thus be compared to them in order to validate the detector performance, as well as to investigate and optimise the sensitivity to various physics processes.

The present chapter describes the algorithms used to simulate, reconstruct and identify physics objects, which are developed and maintained by collective working groups within the ATLAS experiment and are shared by all physics analyses, including the $H \rightarrow \mu^+ \mu^-$ search.

3.1 SIMULATION OF PHYSICS PROCESSES

In ATLAS, simulated samples are typically generated and distributed centrally using perturbative calculations, Monte Carlo (MC) methods and phenomenological models, and reproduce a large number of processes that can cover the needs of most physics analyses and working groups.

The simulation workflow for a given process consists of a sequential chain of three separate steps at different energy scales, which follow closely the way real collision datasets are produced, detected and treated. It begins with the event generation, where all particles expected from a given number of LHC collisions are simulated according to their theoretical predicted distributions. The obtained objects are called truth-level particles, as they are assumed to be known with infinite precision. These particles then enter the detector simulation stage, which models

their interaction with the detector and results in collections of digital signals that resemble those of the raw data. Finally, the digital signals are processed using reconstruction and identification procedures that build physics objects from them, employing the same algorithms used to treat the data collected by the ATLAS detector. The resulting quantities are called reconstructed objects, and take into account the limited precision of the detection and data elaboration processes. At this point, the only difference between simulated and measured events consists of the fact that the MC is known as truth-level, making it possible to look back at the original interactions that produced a given result. This property can be used, for example, to validate the reconstruction algorithms.

The event generation step is performed with the help of various software packages called MC generators. Each of them is able to simulate a defined set of phenomena at a given approximation order using models that are unique to the chosen toolkit, making them suitable for different physics analyses. The detector simulation relies on algorithms that combine a simplified description of its geometry and materials, with models of the interactions of various types of particles. As a consequence the simulated samples, called full-simulation (FullSim) samples as they derive from the complete ATLAS simulation chain, come with a series of associated uncertainties that depend on the theoretical and structural assumptions made, and that impact the experimental studies.

MC simulation is a computationally demanding task and more accurate results can only be achieved at the expense of larger resources. To optimise time consumption, the production usually begins before data taking and is organized in different campaigns, each one aiming at emulating specific conditions of the detector and of the LHC. These must then be matched through further processing and calibrations based on the measured data. The time required to produce a single FullSim event varies widely depending on characteristics such as the number of particles involved, and often a very large number of events is needed. As this is not always achievable within reasonable time scales, alternative fast-simulation (FastSim) algorithms at progressive levels of simplification can be occasionally employed. FastSim samples are produced for a limited number of physics phenomena and within a given physics analysis to perform very specific studies, for example to properly constrain the background in studies with a very low number of expected signal events.

3.1.1 *Event generation*

The event generation step simulates all the particles resulting from the interaction of two hadrons within a LHC collision, and iterates the process until a defined number of such interactions is achieved. It follows a sequence of distinct steps, directly modelled on the different aspects that characterise a real $p - p$ collision described in section 1.2.1: the hard scattering, the parton showering, the hadronisation, the hadron decay and the underlying event.

The hard scattering simulates the interaction of two partons, evaluating the kinematic properties and the colour and flavour structure of the incoming and outgoing particles. The initial momenta of the partons are sampled with parton

density functions, and are used to calculate the scattering cross section in terms of matrix elements (MEs), which describe the process mathematically. The PDFs are determined from fits to deep inelastic scattering measurements performed by fixed-target experiments, and exist in a number of sets that differ in the choice of the input data and fit methodologies. The calculations are performed using perturbative theory at various degrees of accuracy, where the MEs are approximated by summing all the possible Feynman diagrams related to the studied process at a given power of the strong coupling parameter α_C . The dominant contribution comes from leading-order (LO) diagrams, which only consider the lowest power of α_C for which non-zero terms are present, while higher-order corrections such as the next-to-leading-order (NLO) include increasing loop corrections or additional emissions of quarks and gluons.

The evolution of the hard scattering is simulated in the parton showering step, which reproduces the cascade of particles that stem from the radiating initial- and final-state partons using an approximate perturbative treatment at decreasing energy scales, down to some cut-off value of the order of 1 GeV where perturbation theory can no longer be employed. This is done in sequential stages of recursive branchings, carried out following a specific ordered pattern of emissions that depends on the kinematic requirements of the algorithm that emulates the showering. The result is a set of point-like coloured particles, characterised by their momenta and positions and often close to each other within collimated cones.

The following hadronisation step operates at scales where α_C becomes large and perturbative methods can no longer be applied. It simulates the formation of hadrons starting from the partons present at the end of the showering, with the aid of dedicated numerical calculations. Such calculations are based on phenomenological models, which contain a number of parameters that need to be extrapolated from measurements. The two most used models are the Lund string model [75], which connects quark-antiquark pairs through strings that define a hadron if their energy is low enough, and the cluster model [76], which combines gluons, quarks and antiquarks into clusters of neutral colour charge that correspond to hadrons. The resulting particles can be stable, or can decay producing further hadrons, leptons and photons. The hadron decay step invokes effective theories based on perturbative QCD and electroweak calculations or simple symmetry arguments to predict the decay products and branching ratios and generate the related quantities.

Finally, the underlying event step takes into account all the remaining objects that are produced concurrently but do not stem from a hard collision. Since the involved processes are mostly soft scatterings that cannot be treated perturbatively, they are simulated by means of phenomenological models tuned to measured data.

Overall, each simulated event at the end of the event generation consists of a set of particles of different types described by their charges and kinematic properties, and accompanied by the vertices from which they originate. In addition to the final state, also the characteristics of all the intermediate generated objects are provided, such as the momenta of quarks, gluons, gauge bosons and unstable physical particles.

The ATLAS collaboration relies on a pool of various MC generators that can perform one or multiple steps in the event generation. They can be broadly grouped into two classes: pure matrix element generators and general-purpose generators. Pure ME generators only simulate the hard scattering, and their functionality must be interfaced with further algorithms that simulate showering, hadronisation, decays and underlying event. Typical examples of ME generators are MADGRAPH_AMC@NLO [77], and POWHEG [78] with its NLO framework POWHEG-Box [79], which can simulate a wide range of physics phenomena up to the NLO, and ALPGEN [80], which is specialised in hard multi-parton processes and is often used in simulation chains involving multi-jet final states. General-purpose generators, on the other hand, include more complex procedures that are able to take care of the whole event generation. Examples are the SHERPA [81] algorithms, where the hard scattering is modelled at NLO and combined with showering, hadronisation and underlying event altogether, and PYTHIA [82], which is specialised in LO scatterings of parton pairs and recombines hadrons using the Lund string model. Distinct MC generators employ different choices of PDFs and perturbative order in the ME step, and of modelling parameters tuned to the data in the following non-perturbative calculations.

3.1.2 *Detector simulation*

The particles produced during the event generation must be propagated through a simulation of the detector, to mimic its response and provide outputs that reproduce the finite precision of a real measurement. This is accomplished using a geometry and tracking toolkit called GEANT4 [83], which implements a three-dimensional model of ATLAS, including both its sensitive and passive components, and is capable of simulating the interaction of all the generated truth-level particles with the materials of the various subsystems.

The kinematic properties that characterise such interactions are then passed to a digitisation algorithm, which translates them into realistic electric signals to reproduce the output of the detector read-out. The amplitudes and distributions of the signals are calculated on the basis of the functioning of the different sensor types, and include additional smearing to mimic detector noise.

Since the generated samples usually contain only hard scattering events with a predefined outcome, the digitisation stage also takes care of simulating the pile-up, such that the obtained collection of signals is as similar as possible to the corresponding measured data. This is done by injecting additional minimum-bias events, which emulate the effect of multiple soft collisions and are processed with the same triggering procedures used for the data. However, the average pile-up per bunch crossing is a function of the LHC parameters, which are not entirely known at the beginning of a MC production campaign. Precise measurements of these parameters are carried out during each run of the LHC, and are used afterwards to scale the MC to the real data luminosity and pile-up conditions, in procedures called luminosity scaling and pile-up reweighting respectively.

3.2 OBJECT RECONSTRUCTION AND IDENTIFICATION

Different particles interact differently with the ATLAS detector, depending on their type, charge, energy and trajectory. As a result, they exhibit distinct experimental signatures that consist of characteristic patterns of signals. These patterns can be searched for by dedicated algorithms that scrutinise data or simulations to reconstruct and identify the original interacting objects and their properties.

When a charged particle travels through the tracking chambers located in the inner detector and muon system, it interacts with their sensitive components by producing electric signals along its trajectory, called tracking hits. Such hits contain information on one or more spatial coordinates, and can be grouped to create three-dimensional space points. Inside the calorimeters, instead, particles traversing layers of passive material initiate electromagnetic or hadronic showers of decreasing energy, which are detected by cells of active sensors that produce signals proportional to the energy. The resulting calorimeter hits consist of energy deposits associated with the positions of the cells that measured them.

The reconstruction algorithms combine hits into tracks, sum up energy deposits into clusters, and match these quantities to each other in order to transform them into particle candidates and interaction vertices. Candidates of a given particle type are then scrutinised by an identification algorithm, which combines observations from various subsystems in order to discard the so-called fake objects, whose signatures resemble but do not correspond to real particles produced in the event under examination. This is achieved using discriminants that exploit the different expected characteristics of real and fake signals, and cuts on these discriminants define a set of identification working points (WP) that balance different levels of identification efficiency and fake rejection.

Some objects, such as muons, electrons and photons, are also accompanied by a collection of isolation working points that allow to distinguish between prompt particles, directly originating from a hard scattering or resonant decay, and secondary particles coming from subsequent decays within the event or due to pile-up. A particle is considered isolated when there is no additional detected activity in its vicinity, quantified as the total tracker p_T and calorimeter energy found in cones of given radii around the particle, where the contribution of the particle itself is subtracted. Prompt particles are typically expected to be isolated, as they emerge directly from the primary vertex and have higher transverse momentum, and selecting them is helpful in many physics analyses.

The aforementioned isolation and identification working points provide general guidelines for the ATLAS working groups, which can choose the ones that maximise the sensitivity for the signal process they aim to study, depending on their different background sources and rejection needs. With the same goal, additional analysis-dependent cuts on the properties of the identified particles can be applied, such as requirements on the transverse momenta and on the transverse and longitudinal impact parameters.

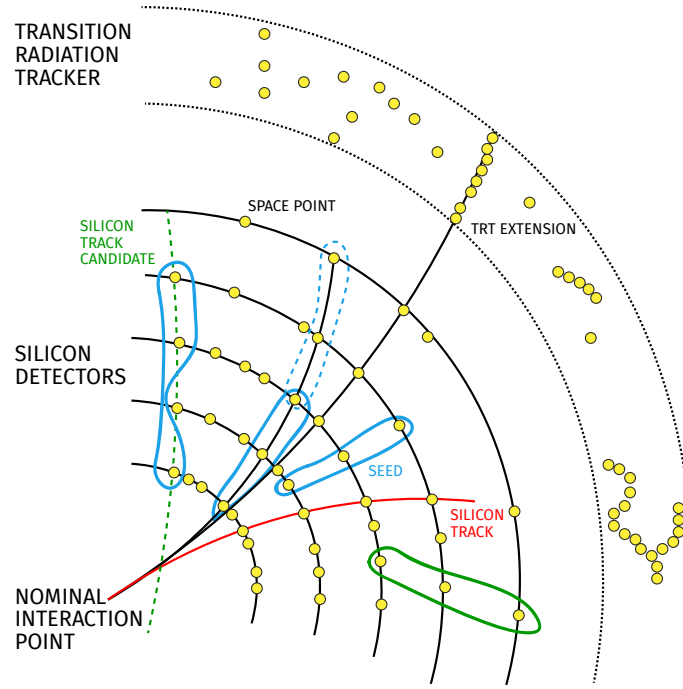


Figure 3.1: Illustration of the track reconstruction procedure in the inner detector. The yellow circles represent three-dimensional space points, and highlighted triplets of them are track seeds reconstructed (blue) or missed (green) by the track finding algorithms. The black curve shows a complete track reconstructed up to the TRT, the dashed green curve is a track not coming from the primary vertex, and the red curve is a track that needs to be extrapolated to the TRT.

A track is parametrized by a minimal set of degrees of freedom referred to as track parameters

$$\left(d_0, z_0, \varphi, \theta, \frac{Q}{p_T} \right) \quad (3.1)$$

that include, from left to right, its impact parameters, the azimuthal and polar angles at its perigee, and the ratio of its electric charge and transverse momentum. Track reconstruction builds these quantities using local and global pattern-recognition algorithms and fitting procedures to combine hits and space points that stem from the same charged object, and to suppress fake contributions by means of quality requirements [84]. Track quality is generally evaluated in terms of the number of hits and the number of holes, where a hole is defined as an active detector element located where a hit is expected by extrapolating the trajectory, but not found¹.

In the inner detector, tracks are reconstructed indiscriminately for all charged particles. The reconstruction procedure, schematically illustrated in figure 3.1, usually starts by combining hits in the silicon sensors that are closest to the center

¹ Inactive modules or regions such as edges between different detector layers are excluded from the hole count.

of the detector, to create space points that provide three-dimensional information. These are used to define a seed, which consists of three space points with compatible values of impact parameters and momenta. Proceeding towards the outermost part of the tracker, different combinatorial algorithms perform the so-called track finding, looking for further points that match the direction of the seed. Multiple track candidates are obtained in the process, and an iterative ambiguity solving procedure is employed to remove those that are incomplete or that can be associated to fake objects, by means of a weighted track scoring and fitting system that takes into account the precision of the various detector technologies. Finally, the resulting tracks are used as inputs to find compatible sets of measurements in the transition radiation tracker by means of a set of extrapolations and refits. Afterwards, a complementary procedure that starts from a TRT seed and proceeds inwards is also employed, to reconstruct tracks from secondary decay vertices and tracks that are shadowed by higher-score ones and were therefore missed by the algorithm that followed the inside-out direction.

High-quality ID tracks with $p_T > 400$ GeV and $|\eta| < 2.5$ are used to reconstruct the vertices of an event, corresponding to the position where the origins of multiple tracks intersect. The vertex candidates are fitted iteratively in order to find the primary vertex of the hard scattering, which is defined as the one associated to tracks with the largest p_T squared sum:

$$\sum_{\text{tracks}} p_T^2. \quad (3.2)$$

In the muon spectrometer, which is optimised for muon detection, a dedicated track reconstruction technique is used, schematically illustrated in figure 3.2. It is based on a procedure that looks for close hits in sensors within the same chamber and combines them by fitting a straight line, creating a track segment. High-quality segments, typically selected in the middle muon layer or station based on their fit parameters, are then used as seeds for the algorithm. Starting from the seeds, an iterative process searches for matching segments in the two remaining muon layers or stations, proceeding both in the inside-out and in the outside-in direction and using fit quality requirements to discard problematic hits. To form a spectrometer track at least two segments are required, with the exception of the transition region between the barrel and the endcaps $1.0 < |\eta| < 1.4$ where a single high-quality segment suffices.

Thanks to the larger distance from the interaction point, the MS deals with lower hit combinatorial noise when compared to the ID. This allows to perform a procedure called hit and segment recovery, which uses precise local track extrapolations and refits to identify possible missed hits or segments and add them back to a given track. The hit recovery first runs a hole search, calculating the intersection of a reconstructed track with the chambers that do not contain hits. Then, it searches for hits in these chambers that are around the intersection, and adds them to the track fit. If more than three MDT hits are found, they are used to create an additional potential segment. The segment recovery looks for compatible additional segments for tracks that are reconstructed without using all three muon

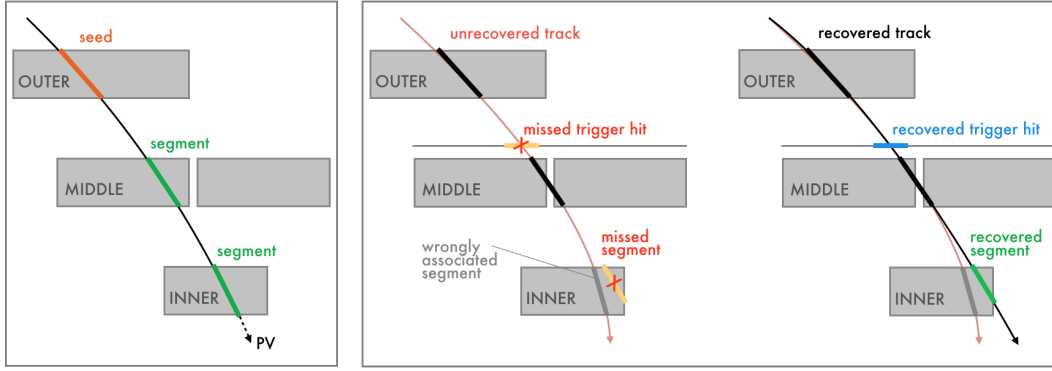


Figure 3.2: Illustration of the track reconstruction (left) and recovery procedure (right) in the muon spectrometer.

stations or layers. This improves the reconstruction performance, providing more robust p_T measurements and increasing the rejection of fake muons since it leads to a more reliable estimation of the number of holes and missed segments that are used as track quality requirements.

Particle momenta are mainly reconstructed from the transverse curvature of their tracks under the influence of the magnetic fields, $\kappa = Q/p_T$, defined as the ratio between their electric charge and the transverse momentum. The accurate measurement and calibration of κ is crucial to obtain the high-precision objects needed by the ATLAS physics analyses. In fact, its value can be influenced by systematic uncertainties due to the limited knowledge and modelling of the detector material, of the magnetic field distribution, of the alignment between the subsystems used to reconstruct the tracks and on imperfections of the reconstruction algorithms themselves. All these factors can in turn affect the p_T estimation by consistently shifting its measurement towards higher or lower values, and thus biasing the overall momentum distribution in an effect known as momentum scale. Additionally, they can increase the uncertainty associated to the single measurements, which translates into a larger width, or worse resolution, of the momentum distribution, and propagates to all the deriving quantities. Among them, the invariant mass spectra, where the resolution of signals coming from resonant decays is affected. To account for these effects, the simulated samples are calibrated by applying a series of correction factors, calculated by comparing data and simulations for well-known processes.

Reconstruction in the calorimeters is performed by grouping neighbouring cells in the longitudinal and transverse direction, on the basis of their position and of the signal they measure. The result consists of a cluster whose energy corresponds to the sum of the total energy deposited in the single cells, calibrated to account for missed cells and dead material. ATLAS employs two types of clustering algorithms: the sliding-window, and the topological clustering [85]. The sliding-window algorithm connects cells within a rectangular window of fixed size, whose position is adjusted to contain a local energy maximum. It is ideal for isolated showers such as those produced by electromagnetic particles. The topological clustering starts with a seed cell, chosen by its signal-to-noise ratio, and iteratively

adds close neighbours with energy above a given threshold, defined as a function of the expected noise. It is an efficient tool when reconstructing hadronic showers that extend over a large number of cells.

After combining all the tracks and energies to reconstruct the visible part of an event, the ATLAS algorithms perform an additional step called overlap removal. The overlap removal identifies candidates that are reconstructed as different objects using the same information, and aims at discarding all potential duplicates. The presence of overlaps can be due, for example, to pile-up and to bremsstrahlung radiation, as well as inefficiencies in the reconstruction procedure. The criteria applied in the overlap removal are specific to a given physics analysis, and aim at ensuring minimal misidentification while maintaining a high acceptance and efficiency for the targeted signal events.

Finally, the event is scrutinised for the presence of missing transverse momentum, a vector quantity that accounts for the momentum magnitude and for the direction in the transverse plane of those particles that traverse the detector without producing any measurable signal. Neutrinos are a typical example, since they interact only weakly and are therefore unable to ionise tracking sensors nor to initiate showering in the calorimeters, but other hypothetical inert particles might contribute as well. Although both these categories of objects are technically invisible, their properties can be inferred from conservation laws if the visible part of an event is accurately reconstructed. In fact, since proton beams collide head-on the centre-of-mass of a hard $p - p$ scattering can be assumed to be stationary, meaning that the total transverse momentum is zero. And since the total momentum of a system is conserved, also the vector sum of all the transverse momenta after a collision, including both visible and invisible particles, must be vanishing. Therefore the invisible component, or missing transverse momentum, can be calculated as the negative vectorial sum of all the reconstructed transverse momenta:

$$\not{p}_T = \sum_{\text{invisible}} p_T = - \sum_{\text{visible}} p_T . \quad (3.3)$$

In terms of its components $\not{p}_T$ can be written as

$$\not{p}_T = \begin{pmatrix} \not{p}_x \\ \not{p}_y \end{pmatrix} = \begin{pmatrix} \not{p}_T \\ \phi \end{pmatrix} , \quad (3.4)$$

where $\not{p}_{x,y}$ are its components in the two transverse directions, $\not{p}_T = |\not{p}_T| = \sqrt{(\not{p}_x)^2 + (\not{p}_y)^2}$ is its magnitude and $\phi = \arctan(\not{p}_y/\not{p}_x)$ is its azimuthal angle.

3.2.1 Electrons

Electrons are charged particles that interact with the ATLAS detector by ionising its tracking sensors, and that can shower producing further electrons and photons in the electromagnetic calorimeters. They can lose a significant fraction of their

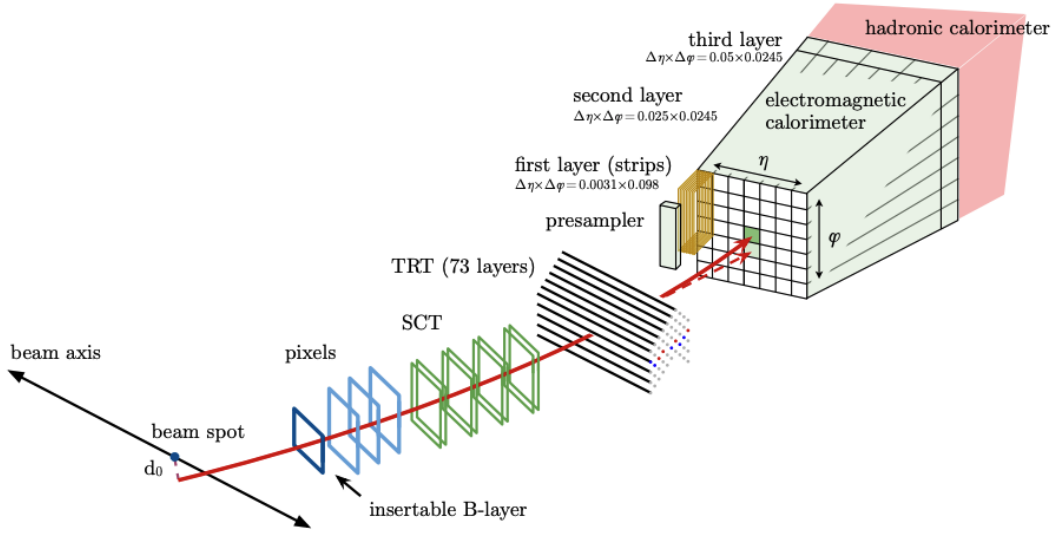


Figure 3.3: Illustration of the trajectory of an electron (red curve) through the ATLAS detector. The dashed red line indicates the path of a photon produced by the interaction of the electron with the material in the tracking system [86].

energy through bremsstrahlung radiation, emitting collimated photons that deposit energy in the calorimeter cells adjacent to those of the original track. Such photons can undergo a process called conversion, in which they transform into pairs made of an electron and a positron that produce two additional charged particle tracks.

As shown in figure 3.3, ATLAS reconstructs electrons by matching showers detected by the EMCal to tracks in the ID, where the latter are crucial in order to distinguish them from non-ionising particles such as photons [86]. For this reason, the reconstruction is performed exclusively in the region covered by the inner detector, $|\eta| < 2.47$, and the uninstrumented area corresponding to the service and cooling systems $1.37 < |\eta| < 1.52$ is excluded.

The information collected by the electromagnetic calorimeter is fed to a specialised algorithm that uses a series of pattern-recognition and fitting procedures to build topological clusters called superclusters, which include the energy deposits coming from a primary electron and the associated satellite deposits produced by bremsstrahlung photons or electrons-positron pairs originating from photon conversion. The superclusters are then matched to tracks in the inner detector through a fitting routine that takes into account their relative position and transverse momenta. A track is matched if it has a $p_T > 1$ GeV and lies within an angular distance of $\Delta R = 0.3$ around the centre of the cluster. If multiple tracks satisfy these conditions, the one that leaves hits in the SCT and has the lowest distance ΔR from the cluster is selected. This procedure creates electron candidates, whose energies are calibrated by comparing Monte Carlo simulations and observed data associated to well-known processes such as $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$ decays [87].

The electron candidates are scrutinised in order to reject fake contributions corresponding to misreconstructed jets that leave energy deposits in the EMCal, and to distinguish prompt electrons from secondary electrons produced in

hadron decays or photon conversions, or due to the pile-up. Jet rejection is achieved thanks to a multivariate identification procedure, which uses information such as the presence of energy deposits in the hadronic calorimeters and the lateral shower width, usually larger in jet backgrounds, as well as the longitudinal energy distribution of the EMCal cluster and the track quality and reconstruction performance, which favour electron candidates. The discriminant consists of a probability distribution that peaks sharply at zero for candidates associable to real electrons, and at one for background objects corresponding to misidentified jets. By applying cuts to this distribution, the ATLAS collaboration defines three working points for a LOOSE, MEDIUM and TIGHT identification in terms of increasing fake rejection at the expense of less efficiency. In particular, the MEDIUM working point used in the $H \rightarrow \mu^+\mu^-$ search requires at least two hits in the pixel detector and seven total hits in the pixel and silicon strip detectors combined, where one of the pixel hits must be in the innermost operational layer.

Distinction of prompt electrons from secondary electrons is achieved in terms of their isolation. In fact, prompt electrons are expected to be isolated in comparison to secondary electrons, which are close to the photon or hadron that produced them. Different isolation working points are defined in ATLAS based on looser or tighter isolation efficiency. For example, the FCLoose working point requires the total transverse energy within a cone of size $\Delta R = 0.2$ around the electron candidate to be less than 20% of the transverse energy of the electron candidate in the calorimeter, and the total transverse momentum in a tracker cone of variable size $\Delta R = \min(10 \text{ GeV}/p_T, R_{\max})$ to be less than 15% of the electron momentum, where $R_{\max}$ is the maximum cone size, typically 0.2 or 0.4.

3.2.2 Photons

Photons have no electric charge, hence they do not interact with the tracking sensors but only with the passive layers of the calorimeters, initiating electromagnetic showers very similar to those of the electrons. Moreover, due to conversion the photons can radiate electron-positron pairs that produce distinct secondary vertices and that can contribute additional electromagnetic showers.

To exploit these characteristics and distinguish photons from electrons, the reconstruction of photons in ATLAS proceeds in parallel to that of electrons and involves the same clustering algorithms within the same instrumented pseudorapidity region $|\eta| < 2.47$. Photon candidates are defined as energy deposits in the EMCal that are not directly matched to single tracks in the inner detector, while ID tracks are used to reconstruct potential conversion vertices [88]. The properties of the obtained quantities are used to determine whether an object is a converted photon candidate, if it consists of an electromagnetic supercluster matched to a conversion vertex, or an unconverted photon candidate if neither a conversion vertex nor any track can be matched to the supercluster. Finally, remaining ambiguities are resolved by analysing hit patterns and the transverse momenta of the candidates.

Photon identification aims at distinguishing between prompt photons and secondary photons originating from hadron decay or due to jets that deposit a signifi-

cant fraction of their energy in the EMCal. The identification algorithm employs a series of cuts on calorimetric variables that describe the shape of the electromagnetic showers, such as the longitudinal and lateral development and the amount of energy leaking into the HCal. As a result, two main reference working points are defined, TIGHT and LOOSE, as a function of decreasing fake rejection and increasing efficiency.

In terms of isolation, the ATLAS collaboration provides a variety of working points in order to satisfy the necessities of a large pool of physics analyses. For example, the TIGHT working point requires that the total transverse energy within a cone of size $\Delta R = 0.4$ around the photon candidate, minus a cut-off of 2.45 GeV, is less than 2.2% of the transverse energy of the photon candidate in the calorimeter. Additionally, the total transverse momentum within a cone of size $\Delta R = 0.2$ must be less than 5% of the transverse momentum of the photon candidate in the tracker.

3.2.3 Jets

Jets are showers of particles that fly in a collimated cone around the direction of the quarks or gluons from which they originate. These particles consist mainly of hadrons, but also include a conspicuous contribution of charged and neutral particles produced in the decay of such hadrons or in their interactions with the detector elements. As a result, jets are experimentally the richest objects at the LHC, and interact both with the tracking sensors and with the calorimeters.

In ATLAS, jet reconstruction starts by matching energy deposits in the EMCal and HCal to retrieve topological clusters, which can additionally be combined with multi-particle signals from the ID. The obtained collections of objects are called topo-cluster (EMTopo [89]) and particle flow (EMPFLOW [90]) jet inputs respectively, where the acronym EM indicates that the calorimeter energies are measured at the electromagnetic scale.

A jet candidate can then be reconstructed by feeding an EMTopo or an EMPFLOW input to a sequential recombination algorithm known as the anti- k_t algorithm [91]. It considers all possible combinations of pairs of objects (i, j) within a jet input, and rates them on the basis of their relative distance

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{(\Delta R_{i,j})^2}{R_p^2}, \quad (3.5)$$

where $p_{T,i}$ and $p_{T,j}$ are the transverse momenta of the objects i and j respectively, ΔR_{ij} is their angular separation and R_p is a fixed radius parameter that defines the size of the cone within which the algorithm operates. Candidates i with relative distance smaller than the distance $p_{T,i}^{-2}$ to the beam line are combined iteratively, and combinations whose total distance from the beam line is larger than any internal object separation are considered jet candidates. Different types of jet candidates can be produced, depending on the choice of the inputs and parameters in the recombination. For example, the ANTIK_{T4}EMPFLOW jets are reconstructed using the anti- k_t algorithm with radius parameter $R_p = 0.4$ and EMPFLOW inputs.

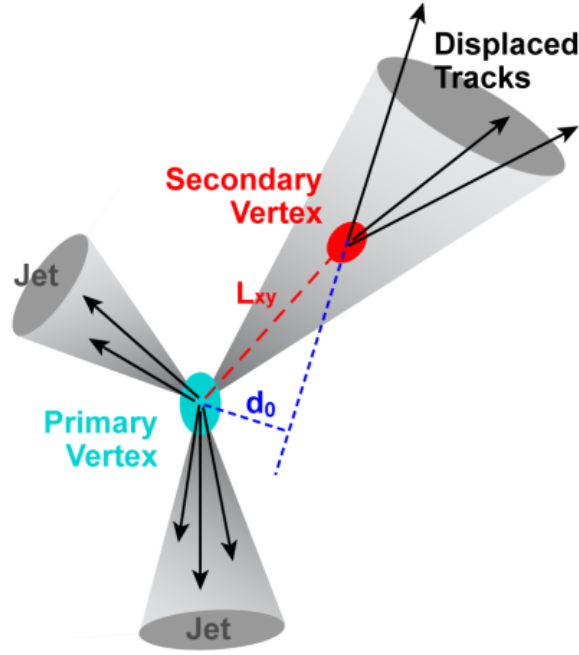


Figure 3.4: Sketch of an event with two light jets coming from the primary vertex and one b-jet produced at a secondary displaced vertex [94].

In general, EMTopo jets exhibit a good resolution across a wide kinematic range and are independent of tracking reconstruction algorithms, while EMPFlow jets take advantage of the precision sensors in the inner tracker to provide better pile-up rejection and p_T and angular resolution, for which they have become the ATLAS default towards the end of Run 2.

After building the jet candidates, their energy must be calibrated by applying a set of corrections in order to take into account the calorimeter scale, the pile-up contribution and potential misreconstructions and detector effects such as the absorption of particles by inert material, or as missing particles that travel outside of the acceptance region [92]. Suppression of pile-up contributions is also achieved thanks to an identification algorithm called jet vertex tagger (JVT), which retrieves and combines tracking information into a multivariate discriminant [93]. For instance, the total p_T of tracks coming from the primary vertex and associated with a jet divided by the total p_T of all jet tracks is used, as it exhibits different distributions for pile-up and jet signal events.

By making use of dedicated criteria it is possible to retrieve the properties of the hadron that generated a given jet, such as its flavour. In particular, bottom quarks always hadronise immediately after their production, while the resulting particles typically have lifetimes of the order of 1.5 ps, which allow them to travel a measurable distance of about 3 mm before decaying. This produces a distinct signature characterised by a displaced secondary vertex matched to tracks that have large impact parameters, as shown in the sketch of figure 3.4. Such signature can be exploited by b-tagging algorithms, which aim at identifying b-jets resulting

from bottom quarks, distinguishing them from jets of different origin, such as those produced by c quarks, gluon fragmentation or lighter particles like τ leptons or u , d , s quarks. The b -tagging first uses a series of low-level procedures based on the impact parameters and on the position of the primary and secondary vertices. Their outputs are passed to high-level algorithms, which combine them into a multivariate discriminant and also take into account kinematic information such as p_T and $|\eta|$. This discriminant is then cut at different selected values, corresponding to specific efficiencies and light- or c -jet rejection factors. For example, the MV2C10 high-level tagger used in the $H \rightarrow \mu^+\mu^-$ search provides two working points, with a 60% and 85% efficiency and a rejection factor of 1200 and 25 for light jets, respectively [94].

3.2.4 Muons

The muons studied by most LHC experiments are in the p_T range up to about 100 GeV, where their energy loss is dominated by ionisation while processes such as e^+e^- pair production, bremsstrahlung radiation and atomic collisions have a negligible impact. As a result, these particles are able to interact with the tracking sensors while flying along trajectories curved by the magnetic fields, but have very limited interactions with the calorimeters and typically traverse them without being stopped.

In ATLAS, muons are therefore reconstructed by relying mostly on the hits that are found in the ID and in the MS, where contributions from calorimetric energy deposits can also be added when needed. The reconstruction is first performed by building tracks separately in the inner tracker and in the muon spectrometer, employing the dedicated algorithms and fit quality requirements already described in section 3.2. The tracking and calorimeter information is then used in different ways to reconstruct four distinct types of muon candidates: combined (CB), segment-tagged (ST), calorimeter-tagged (CT) and extrapolated (ME) [95].

Combined muons use inner tracker and muon spectrometer measurements. They are generally reconstructed by extrapolating MS tracks towards the center of the detector and matching them to ID tracks, exploiting the lower number of MS candidates to minimise the amount of combinatorics. Alternatively, if the MS coverage is found to be poor, they can be built by extrapolating ID tracks in the inside-out direction towards the MS. During the matching a global refitting procedure is performed, where MS hits can be added or removed in order to improve the track quality. Thanks to the large amount of precise information used to reconstruct them, combined muons provide the best momentum resolution.

Segment-tagged muons mostly rely on the inner tracker. They are obtained by extrapolating ID tracks outwards, and looking for at least one MDT or CSC matching segment in the MS. Fully reconstructed MS tracks are not required, and this allows to recover muons that have low transverse momenta and thus only cross a single MS layer, or muons that travel in regions with reduced acceptance of the muon spectrometer.

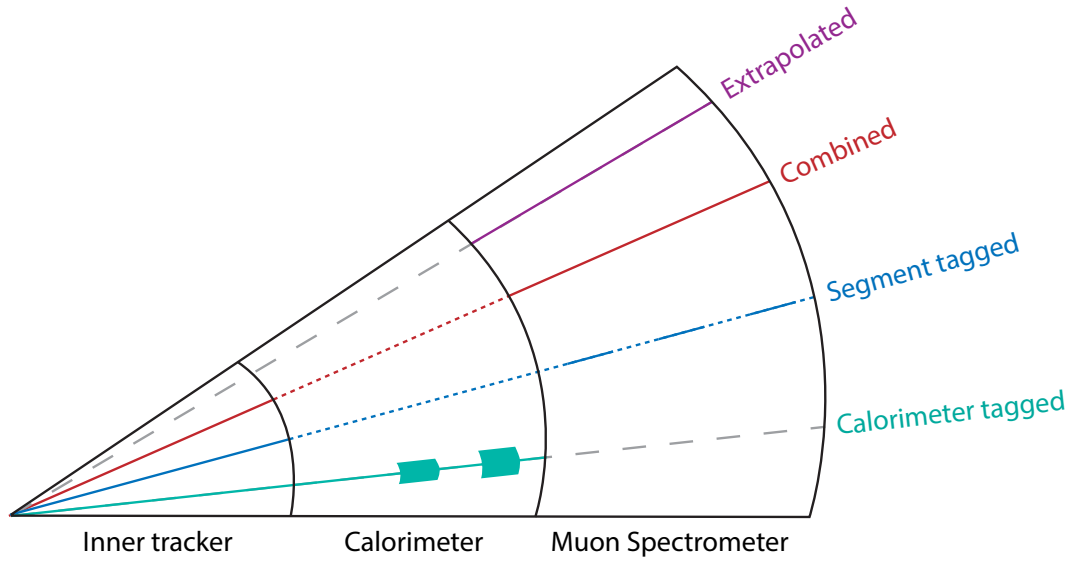


Figure 3.5: Schematic illustration of a transverse section of the muon spectrometer, showing the quantities used to reconstruct the four different muon types.

Calorimeter-tagged muons use only tracks reconstructed in the inner detector, and complement them with calorimeter information. These candidates consist of ID tracks extrapolated outwards and matched to energy deposits in the calorimeter that are compatible with a minimum-ionising particle. Such reconstruction is useful for muons that travel through uninstrumented areas of the MS such as the service region $|\eta| < 0.1$, and that would be otherwise lost.

Extrapolated muons are purely based on the muon spectrometer, and consist of MS tracks projected all the way inwards and matched to the nominal collision point, without including ID information. This procedure allows to recover candidates that travel in the forward direction, outside of the region covered by the calorimeter and inner detector but within the MS acceptance.

The algorithms used to reconstruct the four muon types follow a preferential order based on the quality of the information used, to avoid ambiguities in cases where tracks can be shared by different candidates. Combined muons have the maximum priority, and are reconstructed any time two matching ID and MS tracks are available. Alternatively, when there are no MS tracks that match an ID track, a segment-tagged muon candidate is built, and if no MS segments are present, a calorimeter-tagged muon is provided. When all other options fail, an extrapolated muon candidate is reconstructed from the MS track that has the highest number of hits and the best fit quality. In figure 3.5 a schematic view of the different muon types is shown.

Muon candidates undergo an identification procedure, which serves the purpose of selecting reconstructed objects corresponding to muons originating from a hard scattering, and rejecting background contributions that are mainly due to muons produced in the decay of hadrons not belonging to the event under scrutiny. To achieve this, the ATLAS collaboration provides different working points such as LOOSE, MEDIUM, TIGHT and HIGH- p_T , which balance fake rejection and efficiency.

They are developed using a discriminant built upon reconstruction parameters like the track quality, the number of hits and the value of the transverse momenta measured in the MS and in the ID, based on the fact that muons from hadron decays typically fly at a slightly different direction than that of the original hadron, which produces inconsistent momentum measurements in the ID and in the MS. The **TIGHT** selection maximises fake rejection, and only uses CB candidates with additional quality requirements, the **MEDIUM** criterion includes both CB and ME types and minimises systematic uncertainties while guaranteeing sufficient fake rejection for most physics analyses, and the **LOOSE** working point is designed to maximise the efficiency by including all four muon types found within the $|\eta| < 0.1$ instrumented region of the muon system. Finally, the **HIGH- p_T** selection is defined to identify muons with $p_T > 100$ GeV and improves their overall momentum resolution by imposing additional reconstruction requirements, which deal with the fact that high- p_T muons can lose larger amounts of energy via bremsstrahlung radiation and slightly change their curvature, creating contaminating hits and provoking incorrect reconstructed momentum values. Additional analysis-dependent cuts on the impact parameters can be applied in order to limit contributions from cosmic muons, which constitute a background for most particle detectors [96].

A set of isolation working points is built using variables based on both the tracking and the calorimeter information. The criteria allow to reject fake contributions due to the hadronic punch-through that escapes the calorimeters and produces signals in the muon spectrometer, and to distinguish prompt muons originating from the hard scattering and non-prompt muons coming from secondary vertices, such as those produced in the decay of τ leptons or hadrons. For example, the **FIXEDCUTPFlowLoose** working point requires

$$\max(p_T^{\text{var30}} p_T^{20}) + 0.4 E_T^{20} < 0.16 p_T, \quad (3.6)$$

where p_T^{var30} is the vector sum of all the transverse momenta within a cone of variable size $\Delta R = \min(0.2, 10 \text{ GeV}/p_T)$ around the muon track, p_T^{20} is the total transverse momenta within a cone of size $\Delta R = 0.2$ around the muon, and E_T^{20} is the total transverse energy within a cone of size $\Delta R = 0.2$ around the muon cluster. Only tracks that can be loosely matched to primary vertices are used in the calculation.

The muon reconstruction and identification efficiencies are measured by comparing data and simulated samples of decays such as $Z \rightarrow \mu^+ \mu^-$ with a method called tag-and-probe, where one muon is used to tag an event, and the other is used to perform efficiency measurements. Additionally, the muon momentum scale and resolution are studied with the help of well-known processes such as $Z \rightarrow \mu^+ \mu^-$ and $J/\Psi \rightarrow \mu^+ \mu^-$, and provide correction factors used to calibrate the simulated samples. In figure 3.6 the transverse relative momentum resolution is shown as a function of the truth-level transverse momentum for simulated muons of different types. Matching ID and MS tracks provides the best overall performance thanks to the combination of the high precision and granularity of the ID with the longer arm and higher magnetic field in the MS. The former result in better resolution for

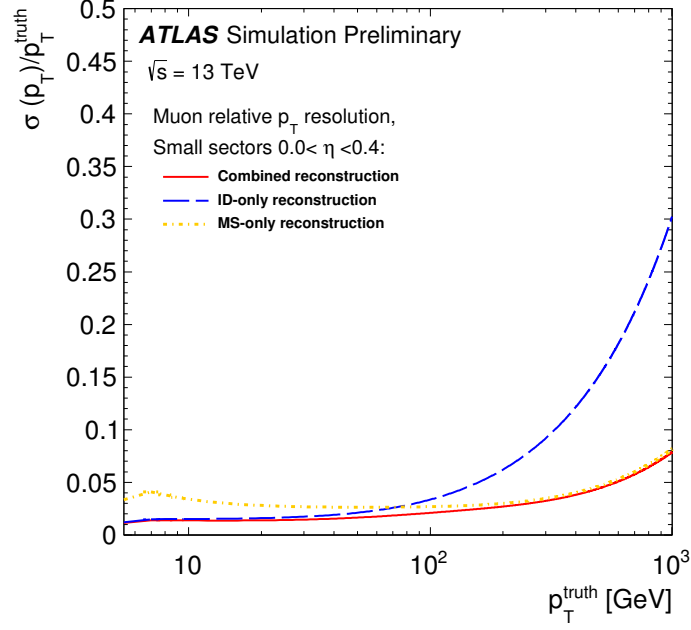


Figure 3.6: Transverse relative momentum resolution $\sigma(p_T^{\text{truth}})/p_T^{\text{truth}}$ as a function of the truth-level transverse momentum for simulated muons in the range $|\eta| < 0.4$ and in the φ regions corresponding to the small sectors of the MS. The resolution is estimated from a Gaussian fit of the truth-to-reconstructed $\kappa = q/p_T$ ratio obtained using combined MS and ID tracks (solid red line), only ID tracks (blue dashed line) and only MS tracks (yellow dotted line) [97].

low- p_T muons dominated by multiple scattering, and the latter allow to measure reliably the small curvatures of high- p_T muons.

3.2.4.1 Outlook on muon reconstruction

The muon reconstruction and identification algorithms need to be updated in order to accommodate the LS2 physical upgrades of the muon spectrometer described in section 2.2.4.1. The foreseen changes involve the replacement of the current endcap inner stations with two new small wheels that, despite being of compatible shape and size as the current configuration, employ two completely new detector technologies. As a result, while part of the software already in place can be recycled profiting from geometric similarities, many of its pieces must be adapted or entirely purpose-built to take into account the different arrangements and responses of the new sensors. Specifically, the local and global MS pattern-finding procedures, the hit and segment recovery and the matching algorithms that create combined muons from MS and ID tracks must be revisited, as well as the event generation and digitisation, which require the introduction of new parameters that keep track of MM and sTGC measurements. Moreover, all these implementations must be carefully tested and validated with the help of fast simulations that mimic the

future behaviour of the sensors and allow to study the performance of the updates. A dedicated working group, the NSW reconstruction group [98] is tasked with taking care of all the needed steps, as described in the following.

MM AND STGC CONTAINERS

Containers that hold the reconstructed quantities related to the new detectors, such as the number of η and ϕ hits and holes, must be provided and included in the central data format of ATLAS, called analysis object data (AOD). These variables are filled following a logic according to which MM and sTGC hits and holes are stored separately, and can be retrieved for further processing. Additionally, obsolete containers such as those for the number of CSC hits and holes are removed, as cathode strip chambers will no longer be used.

DETECTOR GEOMETRY

All track reconstruction algorithms rely on a simplified description of the detector geometry, which allows to perform extrapolation processes and material effects integrations during the pattern-finding and fitting. The geometry is implemented in the ATLAS software via the MUONTRACKINGGEOMETRY package. It includes purely geometric surface classes, which are the base components of all further objects such as the detector volumes and are combined with information on the active and inert materials and on the magnetic field. The surfaces are defined on the basis of a local coordinate system ($locX$, $locY$, $locZ$) and of their shape, which is expressed in terms of geometric boundaries and implemented as a SURFACEBOUNDS object. There are five main different surface types: the cylinder, the disc, the plane, the perigee and the straight line, each with different available boundaries which together are able to describe the entirety of the ATLAS tracking system [99].

When performing track fitting, the coordinate systems used are always the local ones that belong to the surfaces considered. This means that the geometric cut-outs look different in a ϕ measurement, which is carried out by performing a local $\pi/2$ rotation, or in an η measurement, where there is no rotation involved. For this reason, in addition to the basic surface shapes also their rotated versions must be implemented, where the local coordinate system has the $locX$ and $locY$ axes interchanged.

The description of the small wheel geometry during Run 2 is entirely achieved using plane surfaces of trapezoidal shape, which reproduce the cut-outs of TGC, CSC and RPC detector modules and are implemented using the TRAPEZOIDBOUNDS and ROTATEDTRAPEZOIDBOUNDS classes. Trapezoids can still be used for the MM and inner sTGC modules of the new small wheels. However, the outer sTGC detectors in the large sectors are arranged in planes of a different shape referred to as the diamond shape, as shown in figure 3.7. An implementation of this shape already exists under the class DIAMONDBOUNDS to describe other ATLAS components, but it must be included and validated in the MS track reconstruction. Moreover, there is no implementation of the corresponding rotated shape, which must be added to the reconstruction software as a completely new class called ROTATEDDIAMONDBOUNDS.

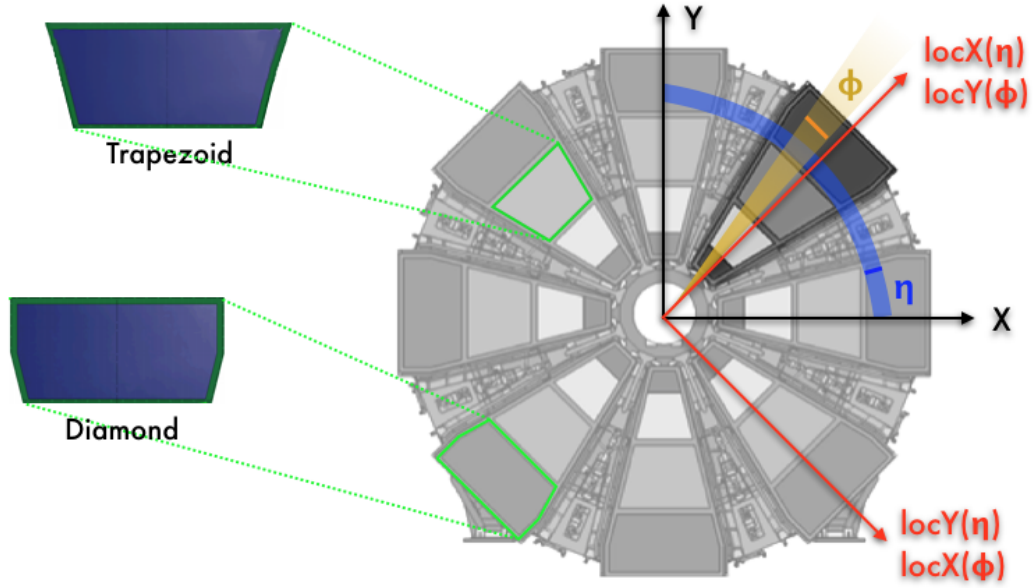


Figure 3.7: Schematic view of the surface shapes needed to describe the NSW large sectors. The global and local coordinate systems are shown in black and red respectively, and the yellow and blue highlighted regions illustrate how measurements of the ϕ and η coordinates can be performed. Adapted from [100].

PATTERN-FINDING AND RECOVERY ALGORITHMS

The crucial part of the muon reconstruction upgrades involves the hit and segment finding and recovery procedures, which have to account for the new geometry and to correctly combine hits in the MM and sTGC sensors, also considering the overlaps between the large and small NSW sectors. To reconstruct MS tracks, a new dedicated pattern-finding algorithm is developed, called `SEGMENTCLUSTERFINDER`. It starts from seeds defined from high-quality segments and begins by using hits in the precision η plane and adding matching ϕ hits afterwards, requiring loose matching to the primary vertex in order to improve the fitting procedures by defining well determined directions. The matching of muon segments among different layers or stations of the MS is also reoptimised to include the improved performance of the NSW.

New recovery algorithms are implemented following the guidelines of the small wheels ones, in order to properly recover hits and segments using the MM and sTGC technologies. The hit recovery is coded in the `MUONCHAMBERHOLERECOVERYTOOL`, while segment recovery is performed by the `MUONSEGMENTREGIONRECOVERYTOOL`. The former identifies holes in chamber layers that already contain other track hits, looks for additional compatible hits and adds them back to the track with a refit. The hole searching functions are added for the MMs and sTGCs based on the existing ones built for the TGCs, which provide similar hit patterns. However, special care is taken in the process: while the MM and the obsolete TGC detectors provide only η hits, sTGCs can provide both η and ϕ hits, and require sequential steps in order to identify the type of measurement. Once hit patterns

are reconstructed, the segment building procedure remains the same. Therefore the segment recovery tool can be directly translated to use MM and sTGC variables in place of the TGC, RPC and CSC ones.

Truth-level muon tracks	No recovery	With recovery	
	Extrapolated	Extrapolated	Combined
Fake	73	54	34
High- p_T fake	52	52	34
Low- p_T fake	3	1	0
Fake trigger	18	1	0
Matched fake	63	53	0
Lost momentum	18	0	0
Missing precision layer	62	16	15
Missing trigger layer	5	0	0
Missing chamber	64	11	6
Wrong precision layer	2	1	1
Wrong trigger layer	0	0	0
Wrong chamber	3	1	1

Table 3.1: Muon tracks reconstructed from a simulated sample containing 1000 events. From left to right: the truth-level characteristic of the track, the number of extrapolated tracks obtained without hit and segment recovery, and the number of extrapolated and combined tracks reconstructed with the hit and segment recovery algorithms in place.

The whole updated reconstruction and recovery chain can be tested using muon tracks simulated with a set of characteristics that are useful to identify the potential issues and improvements introduced by changes in the code. Among these, truth-level tracks with missing segments or hits in precision or trigger chambers, fake tracks at various p_T values, or muon tracks associated to the wrong chambers. For example, results obtained applying the new recovery algorithms on a total of 1000 fast-simulation events that contain muons with transverse momenta in the range 10 – 100 GeV are reported in table 3.1. The procedure is shown to work as expected: the recovered hits lower the number of tracks with missing chambers, and the recovered segments reduce the tracks with lost momentum, which derive from insufficient track curvature due to missing measurements in the innermost muon stations. Additional plots produced with the same simulated samples are shown in figure 3.8, where the numbers of hits and holes reconstructed from MM and sTGC detectors exhibit the expected distributions and ratios.

All the upgrades described above are now functioning and in place, and are ready to be included in the official ATLAS reconstruction software. They contribute greatly to the overall ability of the NSW to cope with the HL-LHC conditions, where the L1 trigger is expected to reduce fake muons by 90% in the forward

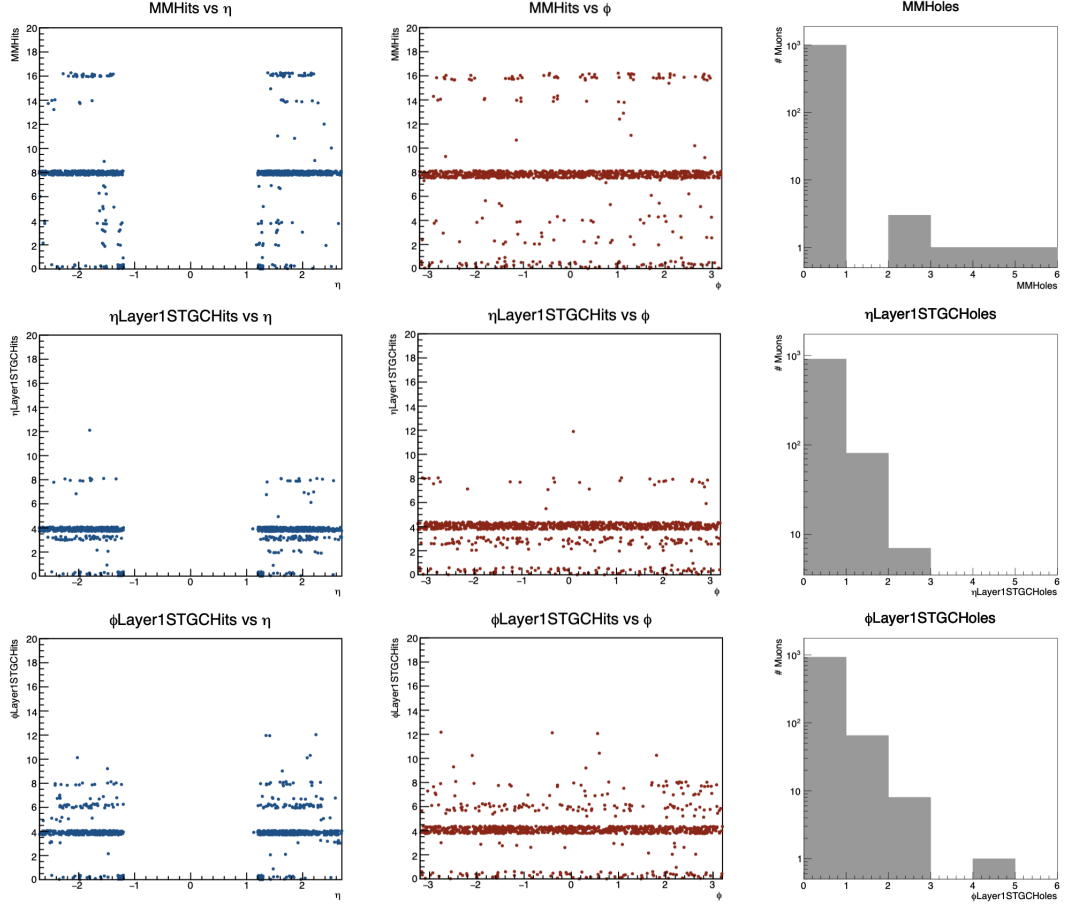


Figure 3.8: Number of η and ϕ hits reconstructed from the NSW detectors as a function of η (left) and ϕ (middle), and inclusive number of holes (right). The top row shows MM quantities, and the middle and bottom row the η and ϕ STGC hits and holes respectively, where STGC counts are shown for only one of the two wedges.

region [101], and the momentum resolution to be better than 15% for muons with a p_T of 1 TeV [102].

3.2.5 Missing transverse momentum

Particles that do not interact strongly nor electromagnetically travel through the ATLAS detector without producing any measurable signal, and are collectively reconstructed as missing transverse momentum. The evaluation of this quantity relies entirely on the proper reconstruction, identification and calibration of the visible part of an event. It involves the sum of two terms, as schematically illustrated in figure 3.9: a hard term that consists of the signals produced by the reconstructed and calibrated particles, and a soft term that includes reconstructed tracks, and eventually calorimeter clusters, matched to the primary vertex but not associated

to any physical object. Adding up these two components, the transverse missing momentum in the x or y direction can be written as

$$\cancel{p}_{x(y)} = - \sum_{\text{hard}} p_{x(y)} - \sum_{\text{soft}} p_{x(y)} . \quad (3.7)$$

Electrons, photons, muons, hadronically decaying τ leptons and jets can all contribute to the hard term, depending on the expected signal topology and on the identification and isolation criteria of a given physics analysis. In order to have a precise $\cancel{p}_T$ estimation it is crucial to identify all these objects and to avoid double counting, therefore an ulterior overlap removal, which takes into account the summation order of the various visible particle types, is performed by the reconstruction algorithm.

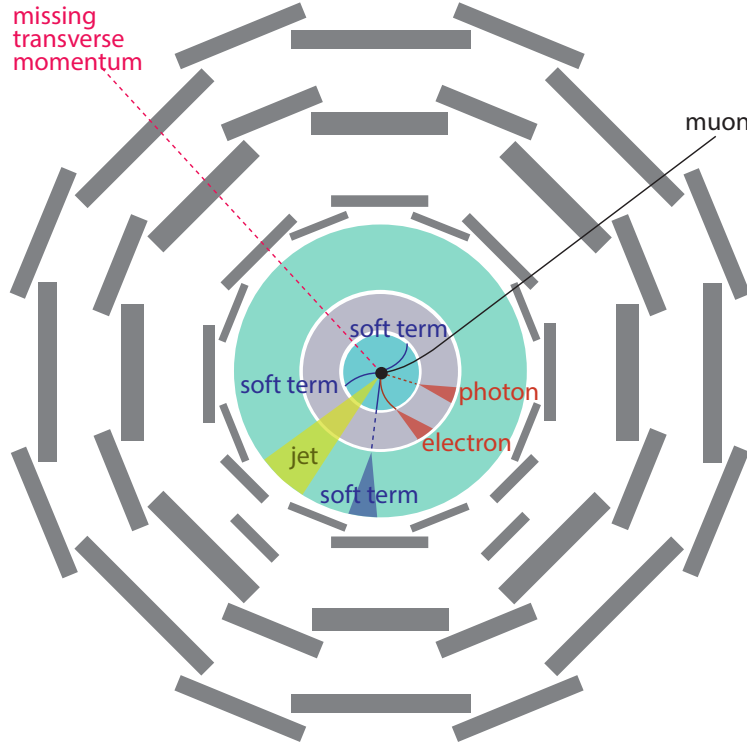


Figure 3.9: Schematic view of a transverse section of the ATLAS detector, where the various hard and soft terms contributing to missing transverse momentum are shown.

The soft term is inserted in the calculation in order to take into account potential inefficiencies in the reconstruction and identification algorithms, but it may also contain unwanted contributions from the underlying event or from pile-up interactions [103]. For this reason, it is generally built only considering tracks from the inner detector but can be made to include calorimeter clusters as well, to recover contributions from neutral objects at the expense of an increased dependence on the pile-up.

Missing transverse momentum is highly affected also by inaccuracies in the momenta estimation, by miscalibrations and by the presence of particles passing

through the uninstrumented regions of the detector, as all of these factors can bias the measured p_T values. To balance pile-up rejection and bias due to potential unused contributions, the ATLAS collaboration provides a series of working points, mostly based on cuts on the jet parameters, since they have the largest impact on the $\cancel{p}_T$ reconstruction. For example, the Loose working point includes all jets with $20 \text{ GeV} < p_T < 60 \text{ GeV}$ and $|\eta| < 2.4$.

The performance of the missing transverse momentum reconstruction is evaluated by studying processes that do not involve invisible particles, such as $Z \rightarrow \mu^+ \mu^-$, where the missing transverse energy is expected to be zero and any discrepancy from this value is due to detector or procedural effects that can be studied in detail.

SEARCH FOR A HIGGS BOSON IN THE DIMUON CHANNEL

To this day, experimental evidence is confirmed for the coupling of the Higgs boson to gauge bosons and to fermions of the third generation. However, its interactions with first- or second-generation fermions have not yet been observed, as they involve much rarer decays in consequence of the smaller lepton masses, and can pose higher detection difficulties related to the presence of light jets.

The dimuon channel represents the best candidate to study the coupling of the Higgs boson to second-generation fermions, offering a clean final state that compensates for its very low branching ratio. In this context, comparing the experimental results with the Standard Model's expectations is a pivotal way of investigating the origin of fermion masses, as any deviation from the predictions could be a sign of new physics.

Searches for the $H \rightarrow \mu^+ \mu^-$ decay have already been performed using the full LHC Run 1 data collected at centre-of-mass energies of 7 and 8 TeV and studying the partial 13 TeV Run 2 data, providing upper limits at 95% CL on the product of the cross section times the dimuon branching ratio. These reach the value of 2.9 times the Standard Model's expectation for CMS [104, 105], and of 2.1 times the Standard Model's prediction for ATLAS [106–108].

This chapter presents a detailed description of the $H \rightarrow \mu^+ \mu^-$ analysis performed on the full set of Run 2 $p-p$ collisions, delivered by the LHC at 13 TeV and collected by ATLAS between 2015 and 2018, for a total integrated luminosity of 139 fb^{-1} that almost doubles that of the previously studied dataset.

4.1 ANALYSIS STRATEGY

The expected topology of a Standard Model dimuon Higgs decay consists of a muon and an antimuon, with possible additional objects generated concurrently to the Higgs boson as anticipated in section 1.2.2. In particular two energetic light jets, emitted roughly in the forward and backward direction with respect to the beam line, are expected in the VBF production mode, while additional jets and leptons

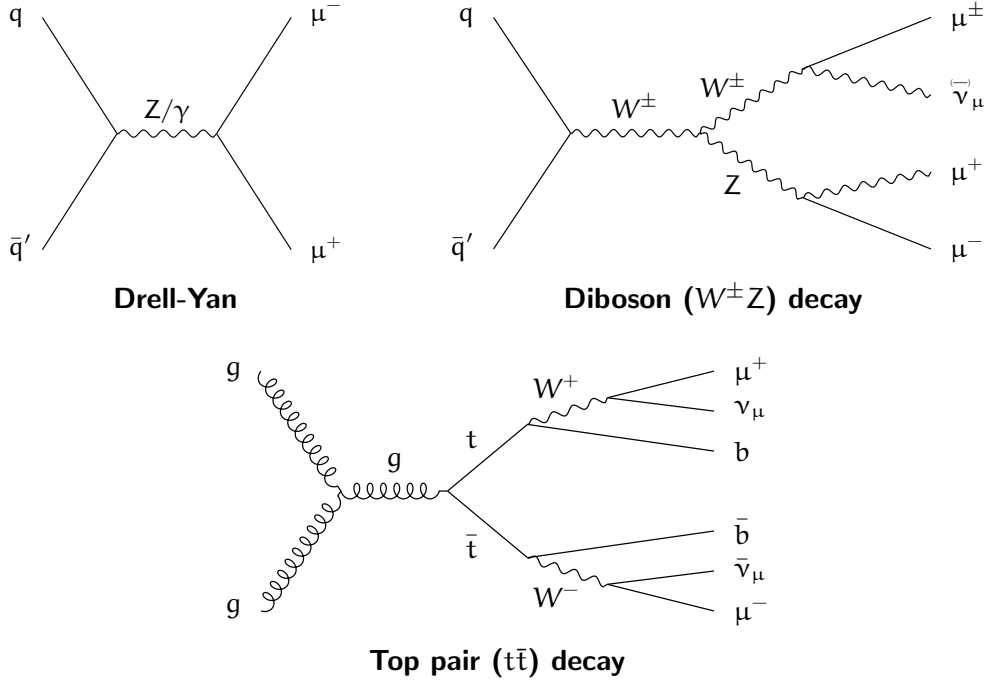


Figure 4.1: Leading-order Feynman diagrams of the main background processes affecting the $H \rightarrow \mu^+\mu^-$ search.

can be present in the $t\bar{t}H$ and VH production modes, deriving from the decay of the $t\bar{t}$ pair and of the weak bosons.

Higgs decays are not the only phenomena responsible for dimuon production. In fact, many different Standard Model processes lead to muon pairs in the final state and thus constitute a background for the $H \rightarrow \mu^+\mu^-$ search. The dominant contribution, when considering all the Higgs production modes inclusively, is due to Drell-Yan (DY) events [109], in which a quark and an antiquark from the colliding protons annihilate and produce a neutral gauge boson that can then decay into $\mu^+\mu^-$. At leading-order, for dimuon masses of around 90 GeV the exchange of a Z boson is favoured, while for higher and lower masses two possible processes, involving a Z boson or a virtual photon respectively, interfere. As a result, the dimuon DY invariant mass spectrum $m_{\mu^+\mu^-}$ consists of a smoothly falling distribution with a resonance peak close to the mass of the Z boson.

The second largest background is due to diboson processes, where at leading-order a quark and an antiquark annihilate generating a $W^\pm Z$, ZZ or $W^\pm W^\mp$ boson pair, whose decay can lead to two muons in the final state.

Also processes that involve the top quark, such as the $t\bar{t}$ production, constitute a background. Since top quarks decay according to the $t(\bar{t}) \rightarrow b(\bar{b})W^+(W^-)$ channel in nearly 100% of the cases, muons can be produced in the final state from the hadronisation of the resulting bottom quarks and from leptonic $W^\pm$ decays.

Example Feynman diagrams of the main aforementioned processes are shown in figure 4.1. Other minor sources can produce additional muons with characteristics

similar to those of the Higgs signal. Among them, the decays of light-flavoured particles within jets, the cosmic background, and QCD processes involving $W^\pm$ +jets, Z+jets and multi-jet production where the jets can be misidentified as high- p_T muons.

The main challenge encountered when searching for $H \rightarrow \mu^+\mu^-$ is given by the the very low branching ratio of this decay channel, especially when compared to the extremely high expected numbers of background events. In the signal region, the theoretical cross section times branching ratio at 13 TeV for the dominant $DY \rightarrow \mu^+\mu^-$ background is 6.7 ± 2.3 pb [110], way larger than the predicted inclusive Higgs production cross section times its muonic branching ratio, $(1.17 \pm 0.13) \times 10^{-2}$ pb [38], leading to a signal-to-background ratio (S/B) of about 0.002. Therefore, the analysis strategy is entirely focused on maximising the number of signal events while suppressing and accurately modelling the background. To achieve this, events are first selected by applying requirements, or cuts, on the multiplicity and properties of the reconstructed objects that they contain, which must match the topology expected in the signal. The selected dataset is then divided into twenty mutually exclusive categories defined using a series of specific criteria and multivariate analysis (MVA) algorithms, which target separately the main ggF, VBF, VH and $t\bar{t}H$ Higgs production modes. Studying each category separately allows to exploit the common characteristics of the events it contains, maximising the sensitivity to the signal.

When a Higgs boson decays into a muon pair, it is expected to appear as a resonance peak in the $m_{\mu^+\mu^-}$ spectrum, corresponding to an excess of events over the SM background localised in the 120 – 130 GeV region around the Higgs boson’s mass, called signal region. The potential excess is quantified by fitting functional forms that model the signal and the background to the observed dimuon spectrum in the window 110 – 160 GeV. This mass range is known as the fit region, and is chosen to guarantee the optimal compromise between signal efficiency and background suppression. The functional forms are chosen empirically in every category, on the basis of the expected shape of the signal and background, and a maximum-likelihood fit is performed simultaneously in each category, relying entirely on the data to extract both the signal and the background contribution. The background yield is estimated by constraining the background model with the data sidebands, which correspond to the 110 – 120 GeV and 130 – 160 GeV $m_{\mu^+\mu^-}$ windows, and then interpolating it in the signal region. Any discrepancy in such region between the obtained background yield and the observed data is then interpreted as a signal. This procedure avoids using simulations to directly estimate the background and thus prevents their potential inaccuracies from affecting the final result, but requires very rigorous background studies, as any mismodelling might pose a bias on the extracted signal.

Another potential bias could be introduced by sculpting the analysis around the signal region, on the basis of prior knowledge or expectations. To avoid this, the selection criteria, the categorisation and the modelling are developed and optimised excluding or, in jargon, blinding, the observed data in such region. Table 4.1 summarises all the $m_{\mu^+\mu^-}$ windows used in the $H \rightarrow \mu^+\mu^-$ search, where the

Region	$m_{\mu^+\mu^-}$ range [GeV]
Z control region	(76, 106)
Signal region	(120, 130)
Sidebands region	(110, 120) $\cup$ (130, 160)
Fit region	(110, 160)

Table 4.1: Summary of the mass regions used in the $H \rightarrow \mu^+\mu^-$ analysis.

Z control region is also defined, corresponding to the 76 – 106 GeV mass range where the physics is well-known and used to validate the performance of the muon selection and momentum resolution by comparing data and MC predictions. Only when the full analysis chain is fixed, validations are performed and all the systematic uncertainties are estimated, the events in the signal region can be added and the final result can be obtained by fitting the full unblinded $m_{\mu^+\mu^-}$ distribution.

4.2 DATA AND MONTE CARLO SAMPLES

The $H \rightarrow \mu^+\mu^-$ search presented in this thesis is performed on the full Run 2 dataset delivered by the LHC, corresponding to $p - p$ collisions collected in 2015, 2016, 2017 and 2018 at the centre-of-mass energy of 13 TeV, for a total integrated luminosity of 139 fb^{-1} .

Besides the measured data, the analysis relies on Monte Carlo simulations for a variety of purposes. MC signal samples are generated centrally by the ATLAS collaboration, following the full ATLAS simulation chain described in section 3.1. They simulate the creation of a Higgs boson from proton collisions according to its main production modes and its subsequent decay into a muon pair, and are used to optimise the event selection and categorisation and to determine the shape of the signal model. Background samples simulate the main Standard Model processes that can lead to final states similar to the signal. Most of them are generated centrally by ATLAS, provide an equivalent integrated luminosity that is typically 5 – 20 times higher than that of the data, and are used to validate the muon momentum resolution and to complement the signal samples in the optimisation of the event selection and categorisation. Additionally, dedicated high-statistics MC samples are generated to contain Drell-Yan events in a much larger number than that computationally achievable using the full ATLAS simulation chain. These are used to develop an accurate functional form for the background model, at the level required by the small expected $H \rightarrow \mu^+\mu^-$ signal.

All the MC samples are subject to pile-up reweighting in order to take into account the effect of multiple collisions in the same or neighbouring bunch crossings. This is done using inelastic minimum-bias $p - p$ events, simulated using PYTHIA 8 with the NNPDF2.3 LO set of PDFs [111] and the A3 set of tuned parameters [112], which are overlayed to the existing MC distributions until the average number of interactions per bunch crossing matches that observed in the data. Finally, the

MC events are corrected with scale factors determined in the sidebands region, to reflect the data momentum scale and resolution, as well as the efficiency of the trigger and of the object reconstruction and identification procedures.

4.2.1 *Signal samples*

The simulation of signal samples is performed using a set of various matrix element generators, which produce parton-level events at different approximation orders, interfaced with the PYTHIA 8.2 program [113] that simulates the parton showering, the final-state radiation, the hadronisation and the underlying event, as well as the decay of the Higgs boson at different accuracies of the QCD processes and of the electroweak corrections. The mass of the Higgs boson is set to $m_H = 125$ GeV in the generation process, with a corresponding width of $\Gamma_H = 4.07$ MeV [114], and the obtained signal samples are processed through the detector simulation operated by GEANT4, and are normalised to the latest available theoretical calculations of the Standard Model production cross sections [39] and to the $H \rightarrow \mu^+ \mu^-$ branching ratio.

Parton-level ggF events are generated at NNLO using the POWHEG-Box generator [115] and the NNLOPS prescription [116], with the set of parton distribution functions PDF4LHC15 [117]. The same PDF set is used to generate VBF and VH Higgs events at NLO still using POWHEG-Box, where the loop-induced $gg \rightarrow ZH$ is produced at leading-order. Finally, the $t\bar{t}H$ generation is performed at NLO using MADGRAPH5_AMC@NLO [118] with the NNPDF3.0 NLO set of parton distribution functions [119]. When interfacing with PYTHIA 8, the AZNLO set of tuned parameters [120] is used for ggF, VBF and VH, and the A14 parameters [121] are used for $t\bar{t}H$.

The ggF sample is normalised to its NNNLO QCD cross section with NLO electroweak corrections [122], the VBF sample is normalised to its NNLO QCD cross section with NLO electroweak corrections [123], and the VH samples are normalised to cross sections calculated at NNLO in QCD with NLO electroweak corrections [124], with the exception of $gg \rightarrow ZH$ that uses next-to-leading-logarithm (NLL) QCD accuracy. Lastly, the normalisation cross section for $t\bar{t}H$ is taken from a calculation accurate to NLO in QCD, with NLO electroweak corrections [125].

4.2.2 *Background samples*

The dominant $DY \rightarrow \mu^+ \mu^-$ background is mainly simulated using the general-purpose SHERPA 2.2.1 generator [126]. At parton level, the NNPDF3.0 NNLO set of PDFs is used. The simulation proceeds in slices based on the scalar sum of the jet transverse momenta where c and b quarks are filtered out, and results in matrix elements with NLO accuracy for up to two partons, and LO accuracy for up to four partons. The parton showering uses the MEPS@NLO prescription [127], and the sample is normalised to its NNLO cross section prediction. An auxiliary sample is also generated with an identical setup and an additional cut of $m_{\mu^+ \mu^-} > 100$ GeV,

with the purpose of populating the higher invariant mass tails that are relevant for the $H \rightarrow \mu^+ \mu^-$ analysis. With the same setup, a sample that simulates electroweak Z+jets events with up to two additional jets in the final state is produced, at LO accuracy beyond the first two jets.

The diboson decays $W^\pm W^\mp$, ZZ and $W^\pm Z$ are entirely simulated using SHERPA 2.2.1 with the NNPDF3.0 set of PDFs, where only semileptonic and dileptonic decays are targeted. Events with up to one additional parton are generated at NLO, and events with two or three additional partons at LO. Additionally, the loop-induced process $gg \rightarrow VV$ is generated at LO. The cross sections are normalised directly to the SHERPA prediction.

The parton-level $t\bar{t}$ and single-top processes are generated at NLO accuracy using POWHEG-Box with the NNPDF3.0NLO set of PDFs, and interfaced with PYTHIA 8 for parton showering, hadronisation and underlying event using the A14 parameter set, with the mass of the t quark set to 172.5 GeV throughout the simulation. Special treatment is reserved to the $W^\pm \bar{t}$ sample, where the overlap with $t\bar{t}$ events is removed using a procedure called diagram removal [128], and to the $t\bar{t}V$ sample, which is modelled using MADGRAPH5_AMC@NLO at NLO.

4.2.2.1 High statistics Drell-Yan Monte Carlo samples

To provide additional DY samples with a significantly larger statistics than that of the data, two fast-simulation setups are prepared using custom algorithms based on simplified steps that are less computationally heavy and, thus, much faster than the full ATLAS simulation chain. The primary configuration, called SHERPA FastSim, is based on parton-level events generated with SHERPA 2.2.4 [129], using LO matrix elements with up to three additional partons in addition to the muon pair. The algorithm employs the CT14 NNLO set of PDF parameters [130], and is interfaced with PHYTHIA 8 to provide QED and QCD parton showering and hadronisation.

A secondary fast-simulation sample, referred to as the POWHEG+ALPGEN FastSim, includes two parton-level subsets: one simulates $DY + 0, 1$ partons at NLO accuracy and is produced using POWHEG-Box with the CT10 PDF set [131], and the other simulates $DY + 2$ partons at LO accuracy and is generated by ALPGEN [132] using the CTEQ6L1 PDF set [133]. Overlaps between the two subsets are removed and approximate QCD algorithms are used to simulate parton showering, while the contribution of final-state radiation is included using PHOTOS++ [134].

Experimental effects are not simulated in any of the fast-simulation samples. Instead, contributions such as the detector response, the reconstruction and trigger efficiencies and the pile-up are added afterwards with parametrised functions tuned on the full-simulation MC samples or extracted from the ATLAS data. This implementation is able to generate two sets of about 10 – 20 billion events, corresponding roughly to at least 50 ab^{-1} in the kinematic regions relevant to the analysis. Both samples give a good description of the $m_{\mu^+ \mu^-}$ data distribution and of the other observables used to select signal events.

4.3 OBJECT AND EVENT SELECTION

The $H \rightarrow \mu^+ \mu^-$ search looks for dimuon final states. Therefore, muons represent the fundamental particles of the analysis and their detection is crucial. However, other quantities are also included in the study: jets, missing transverse momentum, photons and electrons. All these objects are reconstructed using the algorithms described in section 3.2, and are selected for the present analysis according to the prescriptions and working points that maximise the signal acceptance.

4.3.1 Muons

Muons are reconstructed with the procedure detailed in section 3.2.4, where the LOOSE identification working point is chosen. This prescription allows to retain the most objects within the largest detector volume, such that the maximum number of potential signal events is used. CB muons, obtained matching inner detector and muon spectrometer tracks, are the most abundant, but other muon types are also included in challenging detector regions: ST and CT muons improve the reconstruction efficiency for $|\eta| < 0.1$ where the muon spectrometer has limited coverage, and ME muons only use spectrometer information to cover the $2.5 < |\eta| < 2.7$ region not reached by the inner detector. Each muon is required to have $p_T > 6$ GeV and $|\eta| < 2.7$, such that contributions from pile-up and from the decay of heavy-flavour quarks are suppressed.

Muons are expected to be isolated when produced in a Higgs boson decay. Therefore, an isolation requirement with the FIXEDCUTPFLOWLOOSE working point is applied to suppress fake and non-prompt candidates while maintaining a high efficiency in challenging pile-up conditions. Finally, cosmic muons are suppressed by requiring the match of the muon track to the primary vertex with impact parameters satisfying $|d_0/\Delta d_0| < 3$ and $|z_0 \sin \theta| < 0.5$ mm, where Δd_0 is the uncertainty on the transverse impact parameter. The muon selection criteria are summarised in table 4.2.

Muon selection	
Type	CB, CT, ST, ME
Identification	LOOSE WP
Isolation	FIXEDCUTPFLOWLOOSE WP
Transverse momentum	$p_T > 6$ GeV
Pseudorapidity	$ \eta < 2.7$
Impact parameters	$ d_0/\Delta d_0 < 3$
	$ z_0 \sin \theta < 0.5$ mm

Table 4.2: Muon selection criteria used in the $H \rightarrow \mu^+ \mu^-$ analysis.

4.3.2 Jets

Jets allow to target events where the Higgs boson is produced via vector boson or top fusion, aiding to an improved discrimination between the signal and the background. The $H \rightarrow \mu^+ \mu^-$ analysis uses `ANTIkt4EMPFLOW` jets, which are reconstructed passing `EMPFLOW` inputs to the anti- k_t recombination algorithm with radius parameter $R_p = 0.4$, as described in section 3.2.3. To be selected, jets are required to be within $|\eta| < 4.5$, and their transverse momenta must be larger than 25 GeV in the central region $|\eta| < 2.4$ and larger than 30 GeV otherwise.

The JVT vertex tagger is used to reduce the pile-up contribution, rejecting jets with $|\eta| < 2.4$ and $p_T < 60$ GeV that do not originate from the primary vertex. Furthermore, the `MV2C10` tagger is employed to identify jets produced by hadrons containing a b quark, which are typically expected in the $t\bar{t}H$ process and suppressed in the other production modes. The jet selection criteria are summarised in table 4.3.

Jet selection	
Tranverse momentum	$p_T > 25$ GeV for $ \eta < 2.4$ $p_T > 30$ GeV for $2.4 < \eta < 4.5$
Pseudorapidity	$ \eta < 4.5$
Vertex tagger	JVT > 0.2 for $ \eta < 2.4$ and $20 \text{ GeV} < p_T < 60 \text{ GeV}$
b-jet identification	<code>MV2C10</code>

Table 4.3: Jet selection criteria used in the $H \rightarrow \mu^+ \mu^-$ analysis.

4.3.3 Electrons

Electrons are used in the overlap removal procedure and as additional leptons when targeting the VH and $t\bar{t}H$ production modes. They are reconstructed as described in section 3.2.1, and selected according to the `MEDIUM` identification working point. They are required to have $p_T > 6$ GeV and $|\eta| < 2.47$, excluding the transition regions between the barrel and the endcaps $1.37 < |\eta| < 1.52$, in order for their properties to be measured reliably. For the same reason, electrons tagged as `BADCLUSELECTRON`, meaning that they are reconstructed from a calorimeter cluster containing a faulty cell, are rejected.

Additionally, the isolation requirement that uses the `FCLoose` working point and the cuts on the impact parameters $|d_0/\Delta d_0| < 5$ and $|z_0 \sin \theta| < 0.5$ mm are applied, to reduce the contribution of pile-up or secondary electrons coming from hadronic decays. The electron selection is summarised in table 4.4.

Electron selection	
Identification	MEDIUM WP
Isolation	FCLOOSE WP
Transverse momentum	$p_T > 6 \text{ GeV}$
Pseudorapidity	$ \eta < 2.47$ excluding $1.37 < \eta < 1.52$
Impact parameters	$ d_0/\Delta d_0 < 5$ $ z_0 \sin \theta < 0.5 \text{ mm}$
Quality	Not BADCLUSELECTRON

Table 4.4: Electron selection criteria used in the $H \rightarrow \mu^+ \mu^-$ analysis.

4.3.4 *Overlap removal*

In order to resolve ambiguities due to multiple objects reconstructed from the same detector information, the analysis employs an overlap removal procedure that proceeds in the order summarised in table 4.5. First, redundant leptons are discarded, then the overlap between leptons and jets is handled. An electron is removed if it shares a track with another electron of higher transverse momentum, if it shares an ID track with a muon not of CT type, or if it is found in the range $0.2 < \Delta R < 0.4$ around a jet. A jet is removed if it is within $\Delta R < 0.2$ of an electron or a muon, if it has less than three associated tracks, or if its transverse momentum is less than twice that of a muon when the ratio of the muon's p_T to the scalar p_T sum of the tracks in the jet is larger than 0.7. Finally, a muon is discarded if it is of CT type and shares an ID track with an electron, or if it is within $0 < \Delta R < 0.4$ of a jet that was not removed in the previous steps.

4.3.5 *FSR photons*

Photons are studied as potential constituents of the final-state radiation emitted by the muon pair. The two muons produced in the decay of a Higgs boson can in fact lose a significant fraction of their energy through electromagnetic radiation. As a consequence, the reconstructed dimuon invariant mass is no longer equal to the one of the original Higgs boson. The overall effect on the $m_{\mu^+ \mu^-}$ distribution is that of a broader resonance peak, caused by the migration of part of the events to lower mass values, which is harder to distinguish from the background events and therefore worsens the sensitivity.

The FSR affects predominantly the ggF and VBF production modes, where no additional objects can be used to target signal events. To mitigate the issue, photons are scrutinised in order to find up to one FSR candidate whose p_T can be added to the mass calculation, such that the original invariant mass value can be recovered.

Overlap removal		
Removed object	Reference object	Removal criteria
Electron	Electron	shared track, lower p_T
Muon	Electron	shared ID track, CT type
Electron	Muon	shared ID track
Jet	Electron	$\Delta R < 0.2$
Electron	Jet	$0.2 < \Delta R < 0.4$
Jet	Muon	$\Delta R < 0.2$ $N_{\text{tracks}}^{\text{jet}} < 3$ $p_T^{\text{jet}}/p_T^{\mu} < 2$ and $p_T^{\mu}/\sum N_{\text{tracks}}^{\text{jet}} p_T > 0.7$
Muon	Jet	$0 < \Delta R < 0.4$

Table 4.5: Overlap removal used in the $H \rightarrow \mu^+\mu^-$ analysis. An object is removed if, compared to the reference object, satisfies the criteria indicated in the rightmost column. Multiple rows under the same comparison group represent a logical OR. The order in which the procedure is applied goes from top to bottom in the table.

This is done using the algorithms described in section 3.2.2 in combination with a dedicated method, based on the guidelines detailed in [135].

A FSR photon is selected if its angular distance from a muon is $\Delta R < 0.2$, and its p_T satisfies a linearly increasing threshold that goes from 3 GeV for $\Delta R = 0$ to 8 GeV for $\Delta R = 0.2$, with the aim of reducing the background due to pile-up interactions. If more than one photon passes such requirements, the one with the highest transverse momentum is used. Around 5% of the signal events are shown to have at least one FSR candidate, and their recovery allows to reduce the $m_{\mu^+\mu^-}$ signal width by about 3%.

4.3.6 Missing transverse momentum

Missing transverse momentum helps reducing the contribution of background processes that involve top quarks or diboson decays, where muons that could mimic the Higgs signal are created in association with neutrinos, and is a useful quantity when targeting the VH and $t\bar{t}H$ production modes involving leptonic $W^\pm$ boson decays. It is reconstructed following the prescriptions described in detail in section 3.2.5.

4.3.7 Event selection

A very loose selection is applied to the observed data and simulated samples, which consists of a set of criteria based on the multiplicity and properties of the reconstructed physical objects. Its goal is to maximise the potential Higgs signal by including the largest number of events that match its topology, while guaranteeing good quality of the chosen data. Quality checks discard the data collected during unstable beam or detector conditions and suppress misreconstructed jets. This is achieved by requiring the selected events to pass the `GOODRUNLIST` introduced in section 2.1.2, and vetoing jets on the basis of the calorimeter response, such that the electronic noise and beam halo background are suppressed.

Since a $H \rightarrow \mu^+\mu^-$ signal consists of two reconstructed muons generated by the same parent particle, the selected events must contain at least one reconstructed vertex matched to more than one track from the inner detector, where each track has transverse momentum higher than 0.5 GeV such that it is less likely to have originated from pile-up. If multiple vertices are present, the one whose associated tracks deal the largest scalar p_T^2 sum is considered the primary vertex of the hard interaction.

At least two of the reconstructed tracks must belong to muons of opposite charge. Such muons need to pass a combination of triggers and requirements that impose thresholds on their momenta, pseudorapidity and isolation in order to further suppress fake and pile-up contributions. The lowest unscaled single-muon trigger menus, introduced in section 2.2.5, are used: `HLT_MU20_ILOOSE` or `HLT_MU50` in the 2015 data-taking period, and `HLT_MU26_IVARMEDIUM` or `HLT_MU50` in 2016 – 2018. The `HLT_MU20_ILOOSE` selection requires $p_T > 20$ GeV and isolation variable $p_T^{20}/p_T < 0.12$, while `HLT_MU26_IVARMEDIUM` selects muons with $p_T > 26$ GeV and $p_T^{\text{var30}}/p_T < 0.07$ isolation, as defined in section 3.2.4, where the increased threshold deals with the higher event rates at increased instantaneous luminosity in 2016 – 2018. The alternative trigger `HLT_MU50` is used when isolated muons are not found, and requires $p_T > 50$ GeV that compensates for the lack of isolation. The reconstructed muons must have pseudorapidity $|\eta| < 2.7$ and their transverse momenta must belong to a region of high trigger efficiency, meaning that the more energetic muon, or leading muon, must have $p_T^L > 27$ GeV, while the subleading muon needs to have $p_T^S > 10$ GeV, where the superscripts L and S stand for leading and subleading respectively¹. The criteria of the event selection are summarised in table 4.6.

¹ The trigger decision is based on early muon candidates reconstructed from a limited subset of detector information, and can contain candidates where the full offline-reconstructed muons have a p_T lower than the trigger threshold.

	Event selection
Quality	Pass GOODRUNLIST + no misreconstructed jets
Primary vertex	≥ 1 with ≥ 2 ID tracks of $p_T > 0.5$ GeV
Single muon trigger	$p_T > 50$ GeV $p_T > 20$ GeV + $p_T^{20}/p_T < 0.12$ (2015) $p_T > 26$ GeV + $p_T^{\text{var30}}/p_T < 0.07$ (2016 – 2018)
Muons	At least one $\mu^+\mu^-$ pair $ \eta < 2.7$ $p_T^L > 27$ GeV $p_T^S > 10$ GeV

Table 4.6: Summary of the event selection used in the $H \rightarrow \mu^+\mu^-$ analysis.

4.4 EVENT CATEGORISATION

The selected events are divided into four different sets, based on specific criteria that target the main Higgs production modes separately. Such criteria consist of cuts on the transverse momenta and on the number and types of additional leptons and jets that are present in addition to the dimuon pair. They are performed in a specific order such that orthogonal collections of events are created: the $t\bar{t}H$ process is targeted first, followed by VH and finally by the VBF and ggF production modes.

The obtained sets are then further treated by means of MVA algorithms, which combine the information of multiple discriminating variables in each event to classify it as either belonging to the signal or to the background with a given probability. This allows to exploit the impact of different observables and their possible correlations, providing better classification efficiency with respect to individual cuts. The particular MVA model used consists of boosted decision trees (BDT) from the XGBOOST package [136], which employs a combination of many different classifiers, each one made up of a chain of sequential binary cuts. The criteria with which the cuts must be applied are learned by performing fits to a training sample that contains events of known nature, and the classification model is then applied to the two orthogonal so-called validation and test samples, to tune its parameters and evaluate its performance. To limit the effect of statistical fluctuations a k-fold approach is used, meaning that different data partitions are shuffled k times and used in turn for training, validation and testing and their results are then combined.

Events processed through the MVA are assigned a BDT score, $\mathcal{O}$, which indicates their likelihood to belong to the signal or the background. By applying cuts on specific values of $\mathcal{O}$ it is therefore possible to select configurations in which the signal-to-background ratio is maximised, organising the sets of events into one or more categories. In total, twenty orthogonal categories are obtained, sixteen of

them targeting the ggF and VBF processes, three associated to the VH production, and one for the $t\bar{t}H$ mechanism.

4.4.1 $t\bar{t}H$ category

Following the $t\bar{t}H \rightarrow \mu^+\mu^-$ topology shown in figure 4.2, the $t\bar{t}H$ selection targets semileptonic and dileptonic decays of the $t\bar{t}$ pair where b-jets, light jets and leptons are expected in addition to the muons originating from the Higgs boson. As

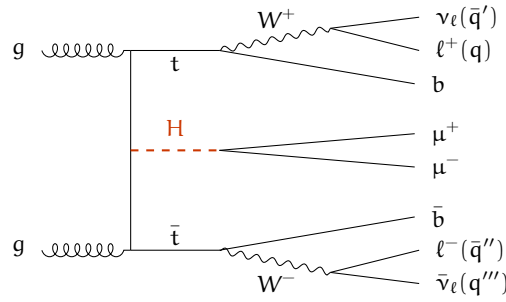


Figure 4.2: Feynman diagram representing the $t\bar{t}H \rightarrow \mu^+\mu^-$ process.

summarised in table 4.7, top fusion candidates are selected by tightening the selection on the muon pair, where the subleading muon must now have $p_T^S > 15$ GeV, and by requiring an ulterior lepton ℓ , being an electron or a muon, with $p_T > 15$ GeV and at least one b-jet tagged using the MV2C10 85% working point.

$t\bar{t}H$ selection	
p_T^S	> 15 GeV
Additional leptons	$\geq 1\ell$ with $p_T > 15$ GeV
Additional jets	≥ 1 b-jet (85%WP)

Table 4.7: Summary of the $t\bar{t}H$ selection used in the $H \rightarrow \mu^+\mu^-$ analysis.

Since t quarks are present in the signal, other QCD processes that involve these particles such as $t\bar{t}Z$ and $t\bar{t}$ decays constitute a significant background for the $t\bar{t}H$ production mode. To suppress it, a BDT classification is trained using simulated events for the $t\bar{t}H \rightarrow \mu^+\mu^-$ signal and for all the Standard Model background processes. The set of discriminating variables used is summarised in table 4.8, and is based on the transverse momenta of the selected objects, on the jet multiplicity, on the muon decay angle [137] and on various invariant mass observables built from the momenta of the decay products.

A cut on the obtained BDT score, $\mathcal{O}_{t\bar{t}H} > 0.35$, is used to create a single $t\bar{t}H$ category that maximises the signal sensitivity while still ensuring enough statistics to constrain the background in the fitting procedure.

t $\bar{t}$ H classification	
Variable	Description
N_{jets}	Multiplicity of jets in $ \eta < 2.5$
$N_{\text{b-jets}}$	Multiplicity of b-jets
$p_T^{\mu^+\mu^-}$	Transverse momentum of the dimuon system
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$(p_T^{\ell_4})$	Transverse momentum of the fourth lepton
$\cos \theta^*$	Cosine of the muon decay angle
H_T	Scalar sum of the transverse momenta of all the jets
$(m_{\ell_3\ell_4})$	Invariant mass of the third and fourth lepton
$(m_{t_{\text{lep}}})$	Invariant mass of the leptonically decaying top quark
$(m_{t_{\text{had}}})$	Invariant mass of the hadronically decaying top quark
$(m_{W_{\text{lep}}})$	Invariant mass of the leptonically decaying $W^\pm$ boson
$(m_{\mu_3^\pm \mu_{1,2}^\mp})$	Invariant mass of third muon and opposite charge muon from H

Table 4.8: Summary of the observables used in the t $\bar{t}$ H BDT classification. Variables within brackets are only used if the correspondent information is found in an event.

4.4.2 VH categories

Events not selected by the t $\bar{t}$ H criteria are considered as potential Higgs-strahlung candidates. As shown by the Feynman diagram in figure 4.3 and summarised in table 4.9, the VH selection targets solely leptonic decays of the associated vector bosons, and is defined separately for the $W^\pm$ and Z case, where a total of three (3 ℓ) and four charged leptons (4 ℓ) is expected respectively. In both cases,

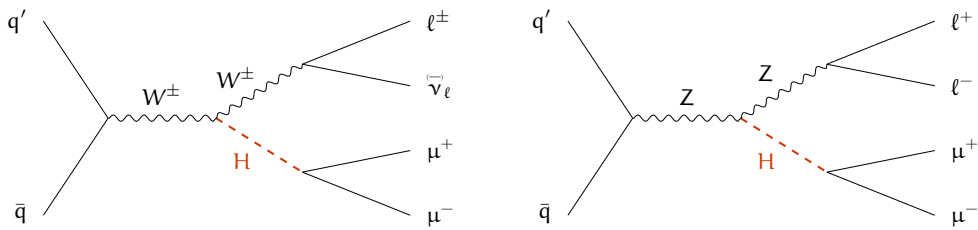


Figure 4.3: Feynman diagrams of the $W^\pm H \rightarrow \mu^+ \mu^-$ (left) and $ZH \rightarrow \mu^+ \mu^-$ (right) decays.

events containing at least one b-jet, identified using the 85% working point of the MV2C10 tagger, are rejected. This allows to suppress top decays, which are the main background contribution besides diboson processes when studying the VH production mode.

VH – 3 ℓ selection	
Additional leptons	1e (μ) with $p_T > 15$ (10) GeV
Additional jets	no b-jet (85%WP)
Additional Z	no $Z \rightarrow \mu^+\mu^-$
VH – 4 ℓ selection	
p_T^S	> 15 GeV
Additional leptons	$\geq 2e$ (μ) with $p_T > 8$ (6) GeV
Additional jets	no b-jet (85%WP)
Additional Z	< 2 $Z \rightarrow \mu^+\mu^-$

Table 4.9: Summary of the VH selection used in the $H \rightarrow \mu^+\mu^-$ analysis.

In the 3 ℓ case, one electron or muon is required in addition to the $\mu^+\mu^-$ pair, with transverse momentum larger than 15 GeV and 10 GeV respectively, and no $Z \rightarrow \mu^+\mu^-$ candidate, defined as an opposite-charge dimuon pair with $m_{\mu^+\mu^-} = (80 - 105)$ GeV, can be present. In the 4 ℓ case the subleading muon originating from the Higgs decay must have $p_T^S > 15$ GeV, and two additional leptons with p_T larger than 8 GeV for electrons and than 6 GeV for muons are required, where at most one $Z \rightarrow \mu^+\mu^-$ candidate can be present. To avoid ambiguities, if the event presents more than two muon pairs overall, their assignment to the $H \rightarrow \mu^+\mu^-$, $Z \rightarrow \mu^+\mu^-$ or $W^\pm \rightarrow \mu^\pm \bar{\nu}_\mu$ decay is based on the electric charge and on the difference between the reconstructed and expected masses of the bosons, taking into account the experimental resolution.

Two distinct BDT classifications are employed for the 3 ℓ and 4 ℓ case. They are trained on Monte Carlo simulations of the respective signals, $W^\pm H \rightarrow \mu^+\mu^-$ and $ZH \rightarrow \mu^+\mu^-$, and of all the Standard Model backgrounds, and use the list of variables summarised in table 4.10 to provide the scores $\mathcal{O}_{3\ell}$ and $\mathcal{O}_{4\ell}$. On the basis of $\mathcal{O}_{3\ell}$, the 3 ℓ events are divided into two categories: VH – 3 ℓ High (VH3LH) if $\mathcal{O}_{3\ell} \geq 0.7$, providing higher signal purity, and VH – 3 ℓ Medium (VH3LM) if $0.1 \leq \mathcal{O}_{3\ell} < 0.7$. Events with four leptons, instead, are only selected if $\mathcal{O}_{4\ell} > 0.12$ and define a single VH – 4 ℓ (VH4L) category.

VH – 3 ℓ classification	
Variable	Description
N_{jets}	Multiplicity of jets
$\not{p}_T$	Missing transverse momentum
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$(p_T^{\text{jet}_1})$	Transverse momentum of the leading jet
$m_{W^\pm}$	Invariant mass of the $W^\pm$ candidate
$\Delta\phi_{\not{p}_T, H}$	Azimuthal separation between $\not{p}_T$ and the H candidate
$\Delta\phi_{\ell_3, H}$	Azimuthal separation between the third lepton and H candidate
$\Delta\eta_{\ell_3, H}$	Pseudorapidity separation between the third lepton and H candidate
VH – 4 ℓ classification	
Variable	Description
N_{jets}	Multiplicity of jets
$(p_T^{\text{jet}_1})$	Transverse momentum of the leading jet
$(p_T^{\text{jet}_2})$	Transverse momentum of the subleading jet
m_Z	Invariant mass of the Z candidate
$\Delta\phi_{\ell_3, \ell_4}$	Azimuthal separation between the third and fourth lepton
$\Delta\phi_{Z, H}$	Azimuthal separation between the Z and H candidates
$\Delta\eta_{Z, H}$	Pseudorapidity separation between the Z and H candidates

Table 4.10: Summary of the observables used in the VH BDT classification. Variables within brackets are only used if the correspondent information is found in an event.

4.4.3 VBF and ggF categories

Events not assigned to the $t\bar{t}H$ or VH categories are considered as candidates for dimuon decays of a Higgs boson produced according to the ggF and VBF mechanisms, whose Feynman diagrams are shown in figure 4.4. To be selected,

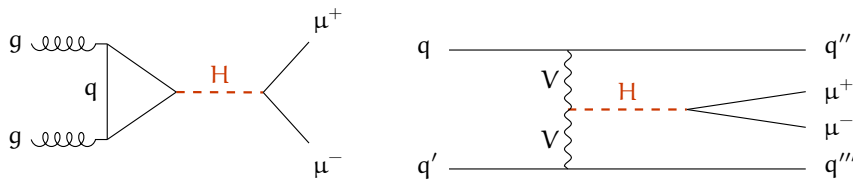


Figure 4.4: Feynman diagrams for the ggF (left) and VBF (right) production of a Higgs boson that decays into a muon pair.

such events must not contain any additional muon with $p_T > 15$ GeV nor b-jet identified with the 60% working point of the MV2c10 algorithm, and the p_T^S of the

VBF and ggF selection	
p_T^S	$> 15 \text{ GeV}$
Additional leptons	no μ with $p_T > 15 \text{ GeV}$
Additional jets	no b-jet (60% WP)

Table 4.11: Summary of the VBF and ggF selection used in the $H \rightarrow \mu^+ \mu^-$ analysis.

subleading muon must be larger than 15 GeV. These requirements are summarised in table 4.11.

Candidates that pass these criteria are divided into three channels according to the number of light jets N_{jet} they contain: the 0-jet, the 1-jet and the ≥ 2 -jet channel. The dominant background contribution in all three cases is given by the Drell-Yan production, and dedicated BDT classification algorithms are trained in each N_{jet} channel to provide its separation from the signal, by exploiting characteristics such as the p_T of the dimuon system, larger in the signal, and the muon decay angle, which is asymmetric for DY events due to the interference between the Z and γ^* processes. According to topological considerations, two light jets are produced in the vector boson fusion mechanism. Therefore, the ≥ 2 -jet channel is expected to contain the majority of VBF events. Here, a specific BDT classification is first applied, trained on VBF $H \rightarrow \mu^+ \mu^-$ decays and SM background simulations and providing the score O_{VBF} . Afterwards, distinct BDT classifications are used on the 0-jet and 1-jet channels, and on the remaining events of the ≥ 2 -jet channel. They are trained on ggF $H \rightarrow \mu^+ \mu^-$ + VBF $H \rightarrow \mu^+ \mu^-$ MC signals and on SM background simulations, and provide the three scores $O_{\text{ggF}}^{N_{\text{jet}}=0,1,\geq 2}$. The complete set of variables used is summarised in table 4.12.

Cuts on the BDT scores, as reported in table 4.13, are used to divide the events into categories. Using O_{VBF} , four distinct VBF categories are defined with decreasing signal-to-background ratios: VBF Very High, VBF High, VBF Medium and VBF Low. Finally, four ggF categories, referred to as Very High, High, Medium and Low, are obtained in each $N_{\text{jet}} = 0, 1, \geq 2$ channel by applying cuts on $O_{\text{ggF}}^{N_{\text{jet}}}$, for a total of twelve categories.

The impact of the categorisation is visualised in figure 4.5, which highlights the signal and background composition in the signal region obtained for each category, as well as the signal purity S/B and the sensitivity proxy $S/\sqrt{B}$.

VBF and ggF classification		
Channel	Variable	Description
Common	$p_T^{\mu^+\mu^-}$	p_T of the dimuon system
	$y_T^{\mu^+\mu^-}$	Rapidity of the dimuon system
	$\cos \theta^*$	Cosine of the muon decay angle
$N_{\text{jet}} = 1, 2$	$p_T^{\text{jet}_1}$	p_T of the leading jet
	η^{jet_1}	η of the leading jet
	$\Delta\phi_{\mu^+\mu^-, \text{jet}_1}$	Azimuthal separation of dimuon system and leading jet
	$N_{\text{tracks}}^{\text{jet}_1}$	Number of ID tracks of leading jet
$N_{\text{jet}} = 2$	$p_T^{\text{jet}_2}$	p_T of the subleading jet
	η^{jet_2}	η of the subleading jet
	$\Delta\phi_{\mu^+\mu^-, \text{jet}_2}$	Azimuthal separation of dimuon system and subleading jet
	$N_{\text{tracks}}^{\text{jet}_2}$	Number of ID tracks of subleading jet
	$p_T^{\text{jet}_1\text{jet}_2}$	p_T of the dijet system
	$m_{\text{jet}_1\text{jet}_2}$	Mass of the dijet system
	$y_{\text{jet}_1\text{jet}_2}$	Rapidity of the dijet system
	$\Delta\phi_{\mu^+\mu^-, \text{jet}_1\text{jet}_2}$	Azimuthal separation of dimuon and dijet system
	H_T	Scalar sum of jet transverse momenta
	$\not{p}_T$	Missing transverse momentum

Table 4.12: Summary of the observables used in the VBF and ggF BDT classification.

Category	0-jet	1-jet	≥ 2 -jet	≥ 2 -jet
	$\mathcal{O}_{\text{ggF}}$	$\mathcal{O}_{\text{ggF}}$	$\mathcal{O}_{\text{VBF}}$	$\mathcal{O}_{\text{ggF}}$
Very High	≥ 0.81	≥ 0.88	≥ 0.93	≥ 0.65
High	$[0.53, 0.81)$	$[0.67, 0.88)$	$[0.85, 0.93)$	$[0.42, 0.65)$
Medium	$[0.21, 0.53)$	$[0.36, 0.67)$	$[0.75, 0.85)$	$[0.16, 0.42)$
Low	< 0.21	< 0.36	$[0.62, 0.75]$	< 0.16

Table 4.13: Summary of the cuts applied on $\mathcal{O}_{\text{ggF}}$ and $\mathcal{O}_{\text{VBF}}$ to define the ggF and VBF categories. Only ≥ 2 -jet events with $\mathcal{O}_{\text{VBF}} < 0.62$ are processed by the $\mathcal{O}_{\text{ggF}}$ classifier.

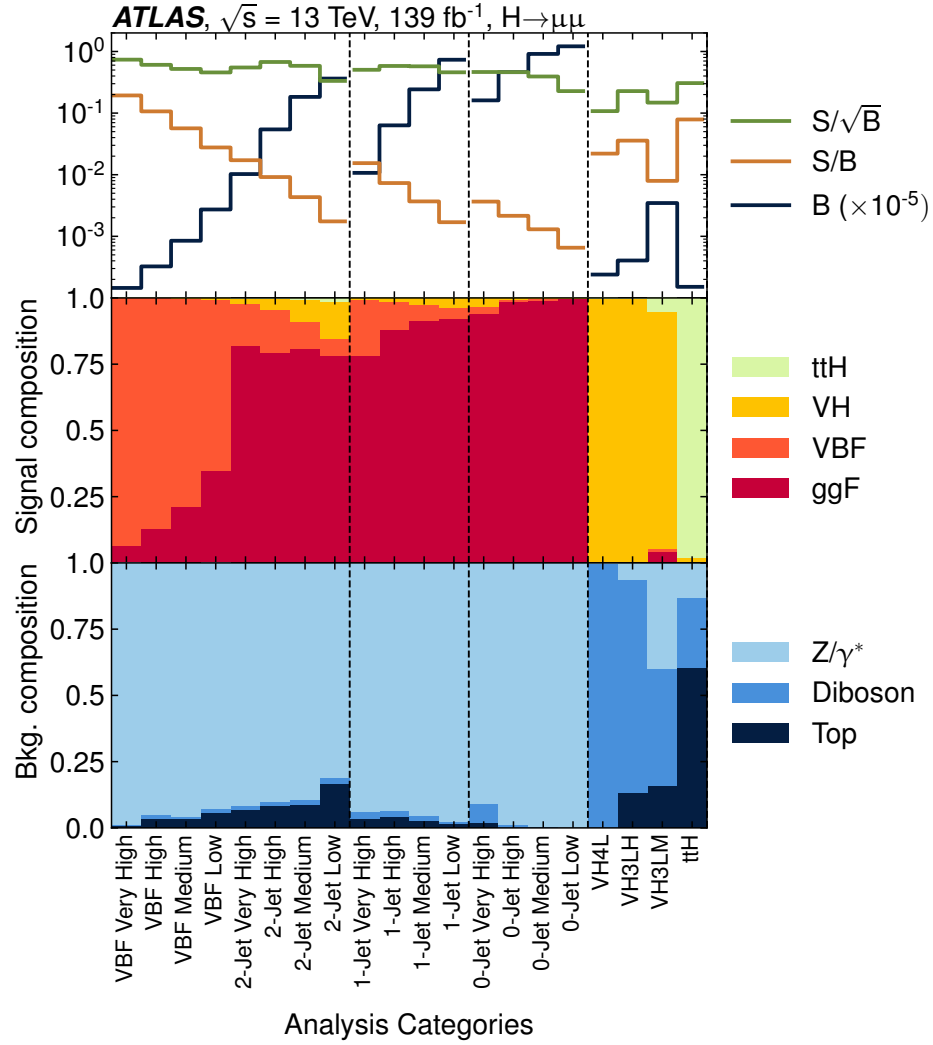


Figure 4.5: Summary of the $H \rightarrow \mu^+\mu^-$ categorisation. The top panel shows the number of background events B , the expected S/B ratio for a SM signal and the counting significance $S/\sqrt{B}$, in the signal region. The middle panel shows the expected contributions of the different production modes, and the bottom panel shows the background composition.

4.5 SIGNAL MODELLING

The width of a Higgs resonance, predicted by the Standard Model to be as narrow as $\Gamma_H = 4.07$ MeV [114], is negligible when compared to the $m_{\mu^+\mu^-}$ resolution of the ATLAS detector, which is of the order of a few GeV [138]. As a result, the experimental shape of the $H \rightarrow \mu^+\mu^-$ signal consists of a peak whose spread around the central value is dominated by the experimental resolution. Additionally, it can be affected by final-state radiation and by phenomenological effects such as the non-Gaussian response of the sensors [139], which produce smaller asymmetric contributions towards lower and higher mass values respectively. All these features can be modelled parametrically with a double-sided Crystal Ball ($\mathcal{CB}$) distribution [140]. It consists of a Gaussian central core [141], which describes the main component of the signal peak, complemented by two power-law tails on both sides that account for the asymmetries. It can be written as

$$\mathcal{CB} = \begin{cases} e^{-\frac{1}{2}t^2} & \text{for } -\alpha_{lo} \leq t \leq \alpha_{hi} \\ e^{-\frac{1}{2}\alpha_{lo}^2 \left[\frac{\alpha_{lo}}{n_{lo}} \left(\frac{n_{lo}}{\alpha_{lo}} - \alpha_{lo} - t \right) \right]^{-n_{lo}}} & \text{for } t < -\alpha_{lo} \\ e^{-\frac{1}{2}\alpha_{hi}^2 \left[\frac{\alpha_{hi}}{n_{hi}} \left(\frac{n_{hi}}{\alpha_{hi}} - \alpha_{hi} + t \right) \right]^{-n_{hi}}} & \text{for } t > \alpha_{hi} \end{cases} \quad (4.1)$$

where $t = (m_{\mu^+\mu^-} - M_{\mathcal{CB}})/\sigma_{\mathcal{CB}}$, with $M_{\mathcal{CB}}$ the mean and $\sigma_{\mathcal{CB}}$ the width of the Gaussian core. The parameters α_{lo} and α_{hi} define the invariant mass thresholds where the Gaussian core transitions to the left- and right-end power-law tails respectively, while n_{lo} and n_{hi} are the power-law orders of the two tails.

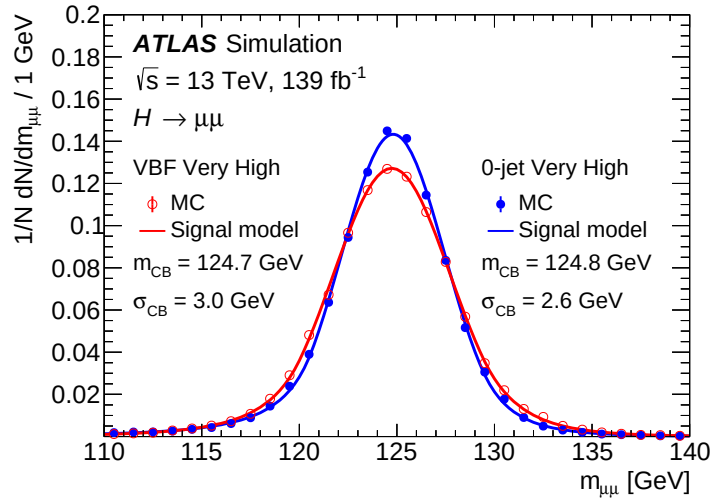


Figure 4.6: Dimuon invariant mass spectra of signal $H \rightarrow \mu^+\mu^-$ events in two specific categories of the analysis, VBF Very High in red and ggF 0-jet Very High in blue. The simulated signal is shown as points, and the fitted parametric signal model is shown as a line.

In a given analysis category, the signal model S^{pdf} can thus be defined as a $\mathcal{CB}$ distribution, with all the shape parameters fixed to the estimates obtained fitting the inclusive signal simulation, which corresponds to the sum of the MC signal samples for all the considered production modes. The obtained values are summarised in table 4.14, and an example of the fits in the ggF 0-jet Very High and VBF Very High categories is shown in figure 4.6.

Category		S	$M_{\mathcal{CB}}$	$\sigma_{\mathcal{CB}}$	α_{lo}	α_{hi}	n_{hi}	n_{lo}
VBF	Very High	3.26	124.74	2.98	1.57	1.57	13.69	4.90
	High	4.04	124.73	2.97	1.39	1.57	13.18	7.26
	Medium	5.61	124.64	2.90	1.39	1.45	20.74	5.16
	Low	8.81	124.66	2.96	1.51	1.54	13.69	3.83
ggF 2-jet	Very High	20.64	124.87	3.11	1.49	1.59	10.95	5.98
	High	57.70	124.74	2.91	1.41	1.54	11.48	5.40
	Medium	91.17	124.63	2.87	1.47	1.65	8.41	3.75
	Low	73.51	124.53	2.87	1.41	1.77	5.88	3.73
ggF 1-jet	Very High	18.75	124.85	2.86	1.59	1.69	7.81	3.85
	High	52.32	124.75	2.75	1.49	1.60	10.49	4.46
	Medium	100.75	124.69	2.71	1.49	1.69	9.04	3.77
	Low	141.43	124.53	2.75	1.47	1.76	8.19	3.23
ggF 0-jet	Very High	65.48	124.81	2.63	1.59	1.74	6.68	2.99
	High	110.20	124.66	2.56	1.51	1.74	8.14	3.12
	Medium	133.66	124.59	2.67	1.43	1.71	9.64	3.66
	Low	89.12	124.55	2.71	1.43	1.79	9.01	4.11
VH	4ℓ	0.63	124.50	2.92	1.30	1.74	6.15	3.21
	3ℓ High	1.74	124.57	3.09	1.50	1.74	7.72	2.10
	3ℓ Medium	3.27	124.50	2.95	1.53	1.76	6.21	1.71
$t\bar{t}H$		1.55	124.59	3.23	1.48	2.02	0.74	1.56

Table 4.14: A summary of the signal yields S and shape parameters obtained by fitting the signal model to the inclusive signal MC in the various analysis categories.

4.6 BACKGROUND MODELLING

The very small signal-to-background ratio in the $H \rightarrow \mu^+ \mu^-$ channel means that the slightest background mismodelling can significantly affect the detection of a signal. In fact if the background model is inaccurate, its discrepancy with respect to the observed data in the signal region can erroneously be interpreted as a signal contribution by the fitting procedure. This contribution is known as spurious signal,

and when undetected it poses a bias on the real signal yield, in a way that is more pronounced for smaller S/B ratios. Therefore, a very rigorous description of the background is of critical importance in the $H \rightarrow \mu^+ \mu^-$ analysis, and mismodellings must be controlled at the per-mille level and accounted for by means of systematic uncertainties.

To achieve this, the background model is constructed by multiplying a rigid core function, common to all analysis categories, with an empirical function specific to each category. The empirical function is chosen using a set of strict criteria based on fits to the data sidebands and to multiple background simulated samples, with which the quality of the models and the associated spurious signals are evaluated. This allows to estimate and minimise the mismodelling, while maintaining enough flexibility to accommodate residual features of the data in the signal region. Additionally, a thorough validation is performed in the most sensitive ggF and VBF categories, in order to further reduce potential inaccuracies related to the choice of the samples used. The validation is not performed in $t\bar{t}H$ and VH categories as their statistical power is limited.

4.6.1 *Choice and preparation of the Monte Carlo samples*

Various MC background samples are used in the background modelling studies, generated both with the fast-simulation setups and the full ATLAS simulation chain as described in section 4.2.2. The sample choice varies with the categories considered and with the type of fitting study performed.

In the ggF and VBF categories, the SHERPA DY FastSim and the full-simulation Drell-Yan, top and diboson backgrounds are employed to evaluate the B-only goodness of fit, while the spurious signal is estimated only on the SHERPA DY FastSim samples, profiting from their high statistics and from the fact that Drell-Yan events represent more than 90% of the total background. The validation cross-checks are performed using the secondary POWHEG+ALPGEN DY fast-simulations, as well as auxiliary samples obtained by applying several theoretical and experimental variations to them, which include changes involving the QCD renormalisation and factorisation scales, the muon momentum resolution and scale, and the usage of alternative PDF sets.

In the $t\bar{t}H$ and VH categories, instead, the dominant backgrounds involve $t\bar{t}$ and diboson decays, while the DY contribution is negligible and subject to large statistical fluctuations. Therefore, full-simulations including only top and diboson backgrounds are used to perform both the B-only fits and the spurious signal evaluation.

Following the event selection and categorisation, distinct analysis categories contain events with different kinematic properties and signal and background distributions. Therefore, a given inclusive luminosity of the MC samples at generation-level does not translate into a uniform population of events in all categories. For example, it ranges from about 20 ab^{-1} to 60 ab^{-1} in the baseline SHERPA fast-simulation sample, not necessarily following the variability expected from the data. This can highly affect the B-only goodness of fit, because higher luminosities enhance

fluctuations that would otherwise be negligible when compared to the required S/B precision, and translates into uneven background modelling criteria among categories. To guarantee uniform rigour, a per-category rescaling procedure is applied to the fast-simulation samples, which are scaled down to meet two minimal requirements based on the MC statistical error on the signal dS_{MC} at 125 GeV: on one hand, dS_{MC} must be smaller than 10% of the data statistical error dS_{data} to keep MC fluctuations under control, and on the other hand it must be smaller than 20% of the predicted Standard Model signal S_{SM} , to make sure that there is no mismodelling that could significantly bias the Higgs signal. The result of the scaling procedure is summarised in table 4.15.

Category	$dS_{\text{MC}}/dS_{\text{data}}$		$dS_{\text{MC}}/S_{\text{SM}}$		$\mathcal{L}_{\text{effective}} [\text{ab}^{-1}]$		
	SHERPA	POWHEG +ALPGEN	SHERPA	POWHEG +ALPGEN	FullSim	SHERPA	POWHEG +ALPGEN
VBF Very High	0.10	0.10	0.15	0.15	0.47	14.00	14.00
VBF High	0.11	0.11	0.20	0.21	1.00	12.00	11.00
VBF Medium	0.10	0.10	0.20	0.19	1.13	14.00	15.00
VBF Low	0.08	0.08	0.20	0.19	1.16	21.00	21.00
ggF 2-jet Very High	0.08	0.09	0.19	0.21	1.33	15.00	13.00
ggF 2-jet High	0.11	0.11	0.21	0.21	1.03	8.00	9.00
ggF 2-jet Medium	0.10	0.08	0.20	0.17	0.84	12.00	17.00
ggF 2-jet Low	0.05	0.05	0.23	0.21	0.69	29.00	35.00
ggF 1-jet Very High	0.08	0.08	0.20	0.19	0.76	17.00	17.00
ggF 1-jet High	0.09	0.09	0.18	0.19	0.45	14.00	13.00
ggF 1-jet Medium	0.10	0.09	0.18	0.18	0.42	15.00	14.00
ggF 1-jet Low	0.08	0.06	0.20	0.20	0.48	18.00	20.00
ggF 0-jet Very High	0.09	0.08	0.20	0.19	0.30	19.00	19.00
ggF 0-jet High	0.08	0.09	0.21	0.20	0.39	16.00	18.00
ggF 0-jet Medium	0.05	0.06	0.20	0.20	0.54	25.00	26.00
ggF 0-jet Low	0.04	0.03	0.23	0.20	1.10	58.00	74.00

Table 4.15: Figures of merit, evaluated at $m_{\mu^+\mu^-} = 125$ GeV, used to rescale the FastSim DY samples, together with the effective luminosity in each category after scaling, compared to that of FullSim.

Afterwards, the $m_{\mu^+\mu^-}$ spectra of the full-simulation and fast-simulation samples are reweighted to the data sidebands. The reweighting is performed by fitting a polynomial function to the data-to-MC (data/MC) ratio and multiplying the MC samples bin-by-bin by the fitted function, such that the main shape discrepancies between data and Monte Carlo are corrected while avoiding picking up statistical fluctuations. A first-order polynomial is used in VBF, $t\bar{t}H$ and VH categories due to limited data statistics, and a second-order polynomial is used for the ggF categories. Examples of the reweighting procedure applied to the baseline SHERPA sample are shown in figure 4.7 for two of the main analysis categories, ggF 0-jet Very High and VBF Very High. It is worth emphasising, nonetheless, that simulations will

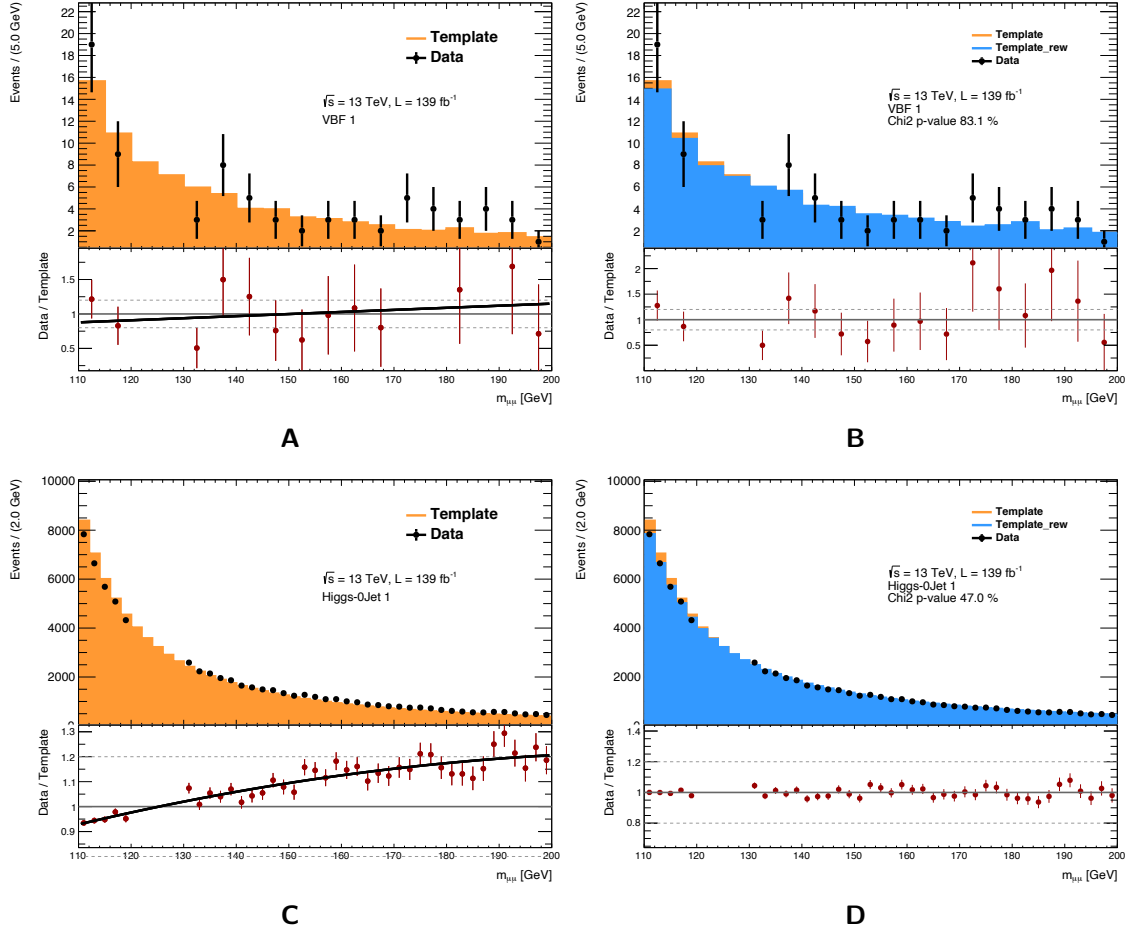


Figure 4.7: Left: fits of the ratio between data sidebands and SHERPA fast-simulations. Right: overlay of the data sidebands and reweighted SHERPA MC samples. (A-B) show the VBF Very High category, (C-D) the ggF 0-jet Very High category.

not be directly employed in the final fitting procedure to evaluate the signal and background yields, but are only used to select background models that are flexible and able to accommodate the real data thanks to their free parameters. Therefore, a perfect agreement with the data sidebands is not essential.

4.6.2 Background model construction

The Drell-Yan process, dominant in most categories, features a steep slope at low $m_{\mu^+\mu^-}$ masses. When combined with $t\bar{t}$ and diboson decays and with other minor background contributions, the resulting overall experimental shape becomes non-trivial to model. To overcome this difficulty, the $H \rightarrow \mu^+\mu^-$ background models are designed as the multiplication of two components: a completely fixed core function F_c , which takes care of the main DY trend, and a flexible empirical function F_E , which aims at describing the remaining difference between the background spectrum and the core, correcting for distortions of the mass shape produced by event

selection, categorisation, higher-order effects and other background contributions, especially in categories where the DY is subdominant.

The core component is a physics-inspired analytical function based on the leading-order Drell-Yan lineshape [142] DY_{LS} , convolved with a Gaussian distribution $\mathcal{G}$:

$$\begin{aligned} F_c &= DY_{LS} \star \mathcal{G} \\ &= \left(\sum_q L_{q\bar{q}}(m_{\mu^+\mu^-}) \sigma_{q\bar{q}}(m_{\mu^+\mu^-}) \right) \star \mathcal{G}(0, \sigma(m_{\mu^+\mu^-})) , \end{aligned} \quad (4.2)$$

where only the lightest quarks $q = u, s, d$ are considered. The Drell-Yan lineshape is given by the product of the parton luminosity distribution $L_{q\bar{q}}$, derived from the PDF4LHC15 PDF set using APFEL [143] interfaced to LHAPDF6 [144], and of the LO Drell-Yan cross section $\sigma_{q\bar{q}}(m_{\mu^+\mu^-})$, whose components can be calculated as

$$\sigma_{q\bar{q}}(m_{\mu^+\mu^-}) = \frac{4\pi\alpha_{fs}^2}{3\tilde{s}N_c} [Q_q^2 - 2Q_q V_\ell V_q \chi_{Z\gamma}(\tilde{s}) + (A_\ell^2 + V_\ell^2)(A_q^2 + V_q^2) \chi_Z(\tilde{s})] , \quad (4.3)$$

where $\tilde{s} = m_{\mu^+\mu^-}^2$ and where

$$\begin{aligned} \chi_{Z\gamma}(\tilde{s}) &= \kappa_Z \frac{\tilde{s}(\tilde{s} - m_Z^2)}{(\tilde{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \\ \chi_Z(\tilde{s}) &= \kappa_Z^2 \frac{\tilde{s}^2}{(\tilde{s} - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \\ \kappa_Z &= \frac{\sqrt{2}G_F m_Z^2}{4\pi\alpha_{fs}} . \end{aligned} \quad (4.4)$$

In the previous equations Q, V and A denote the electric charge and the vector and axial-vector couplings of the fermions respectively, α_{fs} is the electromagnetic fine-structure constant [145], G_F is the Fermi constant, m_Z and Γ_Z are the mass and width of the Z boson with values taken from [146] and $N_c = 3$ is the number of QCD colour charges.

The Gaussian function $\mathcal{G}$ has mean at zero and mass-dependent width $\sigma(m_{\mu^+\mu^-})$ which is estimated as the root-mean-square (RMS) of the dimuon invariant mass resolution, defined as the difference between the reconstructed and truth-level DY FullSim $m_{\mu^+\mu^-}$, and parametrised with a second-order polynomial. This component is needed to model detector resolution effects, which would otherwise significantly distort the background shape at low mass values, as shown in figure 4.8.

Two main families of functional forms are tested as empirical functions F_E , as summarised in table 4.16: power-laws (Power) and exponentials of polynomials (Epoly), with a variable number N of floating coefficients, or degrees of freedom. The multiplication of the core function with each empirical function separately produces a large pool of background models, which are tested separately in each analysis category.

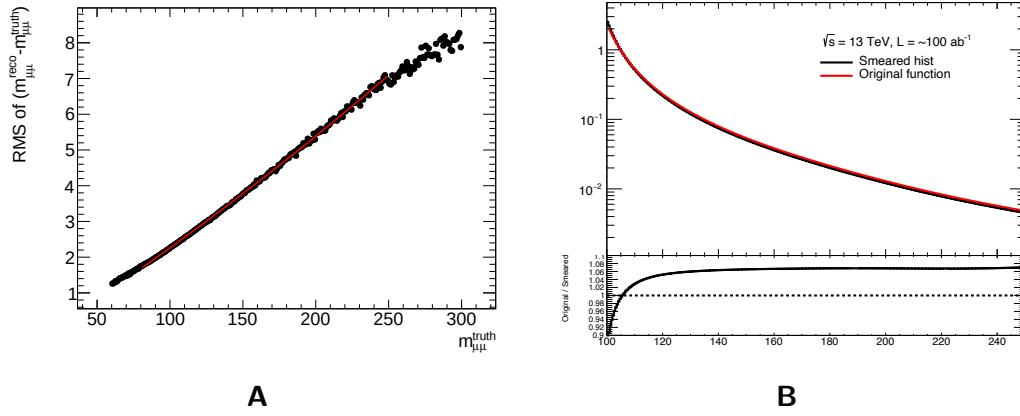


Figure 4.8: (A) Parameterization with a second-order polynomial, shown in red, of the black dots representing the RMS of the dimuon invariant mass resolution $m_{\mu^+\mu^-}^{\text{reco}} - m_{\mu^+\mu^-}^{\text{truth}}$ as a function of the truth-level mass $m_{\mu^+\mu^-}^{\text{truth}}$. (B) Comparison of the core function $F_{\mathcal{E}}$ with (black) and without (red) the resolution effect modelled by $\mathcal{G}$.

4.6.3 Background model selection criteria

A rigid set of sequential criteria is used to select the most suitable background model in each category, as schematised in table 4.17.

First, the B-only goodness of fit is checked: only functions able to describe the data sidebands, the reweighted full-simulation background and, for ggF and VBF categories, the reweighted and scaled fast-simulation SHERPA DY with a χ^2 probability $P(\chi^2)$ larger than 1% are considered. This ensures that the chosen models are flexible enough to account for differences between data and simulation. Examples of the obtained fits are shown in figure 4.9 for the VBF Very High category.

Secondly, a spurious signal test is performed separately in each category, for each function satisfying the previous requirement. It consists of estimating the spurious signal at various values of the Higgs boson's mass, ranging from 120 to 130 GeV in steps of 1 GeV, and picking the obtained maximum, denoted as SS , as a measure of the total systematic uncertainty. The basic principle behind the evaluation of the spurious signal at a given mass step can be outlined as follows: when a signal-free

Empirical function $F_{\mathcal{E}}$	Expression
EpolyN	$e^{(a_1 m_{\mu^+\mu^-} + a_2 m_{\mu^+\mu^-}^2 + \dots + a_N m_{\mu^+\mu^-}^N)}$
PowerN	$m_{\mu^+\mu^-}^{a_0 + a_1 m_{\mu^+\mu^-} + a_2 m_{\mu^+\mu^-}^2 + \dots + a_{N-1} m_{\mu^+\mu^-}^{N-1}}$

Table 4.16: Families of empirical functional forms tested in the background modelling.

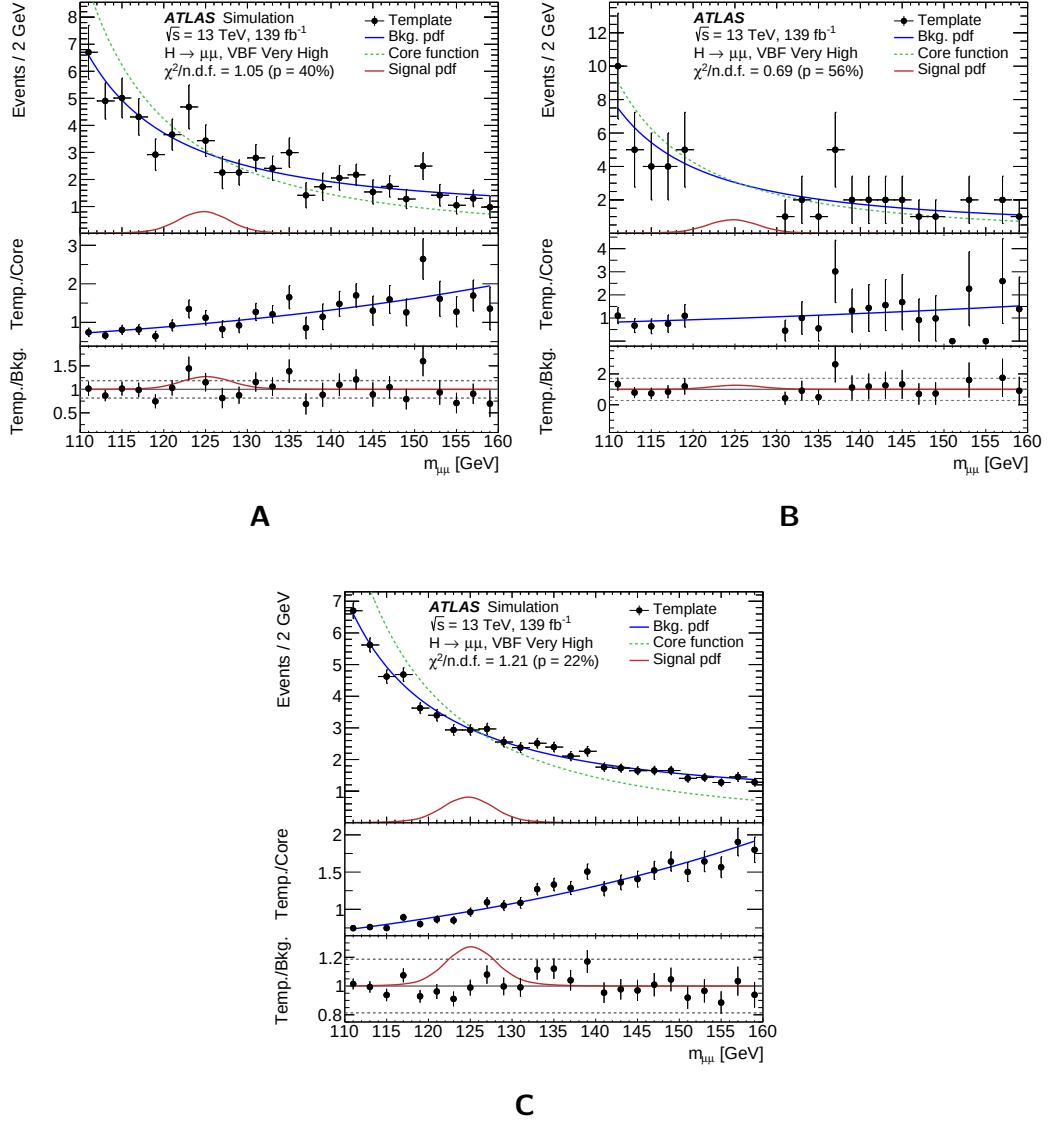


Figure 4.9: Dimuon invariant mass spectra in category VBF Very High, for full-simulation MC background (A), data sidebands (B) and fast-simulation SHERPA DY MC (C), prepared as described in section 4.6.1. The blue line represents the fitted background model and the green dashed line is the contribution of the core, where the middle panel is divided by the core contribution. The red line is the signal model normalized to the predicted cross section, which is divided by the full background model in the bottom panel.

Monte Carlo sample of sufficiently high luminosity such as the ones defined in section 4.6.1 is fitted with the signal+background model

$$S \cdot S^{\text{pdf}} + B \cdot B^{\text{pdf}}, \quad (4.5)$$

the statistical uncertainties are negligibly small and thus any number of fitted signal events S is entirely attributable to the inability of the background model to fully describe the underlying spectrum. In the above formula, S^{pdf} is the signal model described in section 4.5 and B^{pdf} represents the background model under examination, with B the number of fitted background events. To pass the spurious signal test, the studied background function must obey $|SS/dS| < 20\%$, meaning that the maximum spurious signal has to be less than 20% of the expected statistic uncertainty of the data within the full 120 – 130 GeV mass range, where the MC statistical error is taken into account by subtracting it from the SS value. This requirement guarantees that the background mismodelling is smaller than the statistical uncertainty on the signal. Examples of the obtained SS/dS as a function of the Higgs boson's mass are shown in figure 4.10 for the ggF 0-jet Very High and the VBF Very High categories.

Among the functions passing the two previous criteria, those with the smallest number of degrees of freedom are considered, and the one with the lowest absolute value of SS is selected. These final requirements guarantee that the statistical and systematic uncertainties are minimised.

The result of the selection procedure in each category is summarised in table 4.18, and shows that the chosen background functions do not bring any statistically significant mismodelling, as the SS is always less than two standard deviations away from zero. For the same reason, the spurious signal uncertainties are assumed to be uncorrelated. They range from a few per-cent up to about 20% of the expected data

Background model selection criteria	
$P(\chi^2) > 1\%$	
	data sidebands
	FullSim top + diboson + (only ggF, VBF) SHERPA DY
	(only ggF, VBF) FastSim SHERPA DY
$ SS/dS < 20\%$ within MC statistical uncertainty	
	(only ggF, VBF) FastSim SHERPA DY
	(only VH, $t\bar{t}H$) FullSim top + diboson
Smallest number of parameters	
Smallest $ SS $	

Table 4.17: From top to bottom: list of sequential criteria used to select the background model in each analysis category.

Category	B^{pdf}	$\frac{SS}{dS}$ [%]	SS	N	$P(\chi^2)$		
					FullSim	data	FastSim
VBF Very High	$F_C \times \text{Epoly1}$	-10.80	-1.15	1	0.40	0.56	0.22
VBF High	$F_C \times \text{Power0}$	0.80	0.82	1	0.89	0.07	0.51
VBF Medium	$F_C \times \text{Power0}$	0.00	0.92	1	0.29	0.87	0.76
VBF Low	$F_C \times \text{Power0}$	2.95	2.14	1	0.22	0.34	0.96
ggF 2-jet Very High	$F_C \times \text{Power1}$	4.80	-7.24	2	0.06	0.17	0.19
ggF 2-jet High	$F_C \times \text{Epoly2}$	-8.06	-23.80	2	0.63	0.94	0.12
ggF 2-jet Medium	$F_C \times \text{Power1}$	9.95	37.30	2	0.89	0.83	0.48
ggF 2-jet Low	$F_C \times \text{Epoly3}$	0.00	5.91	3	0.17	0.08	0.50
ggF 1-jet Very High	$F_C \times \text{Epoly2}$	14.30	-10.00	2	0.02	0.57	0.38
ggF 1-jet High	$F_C \times \text{Epoly2}$	0.00	-9.70	2	0.69	0.53	0.82
ggF 1-jet Medium	$F_C \times \text{Power1}$	0.00	7.94	2	0.72	0.07	0.85
ggF 1-jet Low	$F_C \times \text{Power1}$	9.00	72.60	2	0.59	0.13	0.12
ggF 0-jet Very High	$F_C \times \text{Power1}$	11.00	33.30	2	0.08	0.12	0.27
ggF 0-jet High	$F_C \times \text{Power1}$	-10.20	47.80	2	0.36	0.34	0.73
ggF 0-jet Medium	$F_C \times \text{Power1}$	18.60	93.00	2	0.62	0.19	0.02
ggF 0-jet Low	$F_C \times \text{Epoly3}$	-16.80	-89.50	3	0.93	0.16	0.03
VH - 3 ℓ High	$F_C \times \text{Power1}$	9.33	1.38	2	0.11	0.23	—
VH - 3 ℓ Medium	$F_C \times \text{Epoly2}$	16.50	3.58	2	0.45	0.03	—
VH - 4 ℓ	$F_C \times \text{Epoly3}$	13.80	9.15	3	0.90	0.61	—
$t\bar{t}H$	$F_C \times \text{Power0}$	14.20	1.87	1	0.19	0.74	—

Table 4.18: Summary of the background models B^{pdf} selected in each analysis category, together with the values of the figures of merit used to select them. The values reported for SS/dS include the MC statistical error, and the baseline SHERPA FastSim is used.

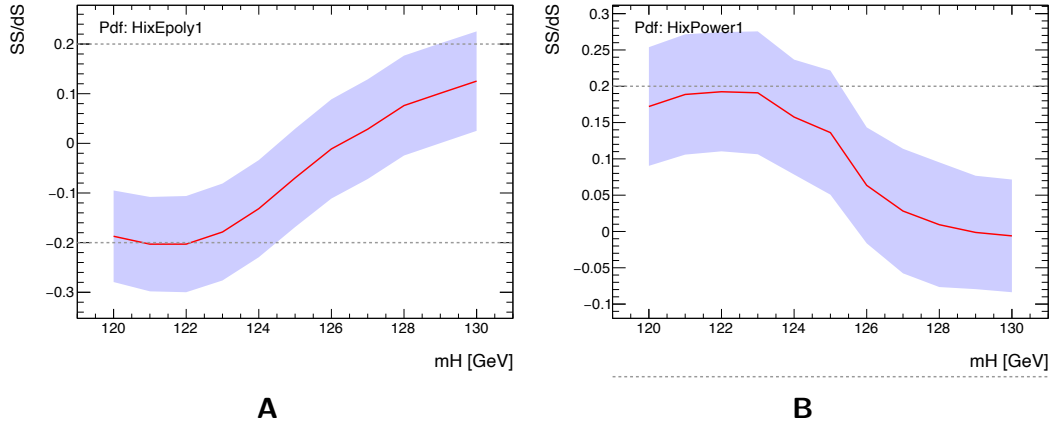


Figure 4.10: Distribution of the SS/dS value, in red, as a function of the Higgs boson's mass, obtained fitting with the chosen background models B^{pdf} in the VBF Very High (A) and ggF 0-jet Very High (B) categories. The bands represent the MC statistical error, and the dashed grey lines show the 20% limits within which SS/dS is required to be.

statistical error in all categories, including VH and $t\bar{t}H$, where the full-simulation samples used to evaluate SS have less statistical precision.

4.6.4 Stress tests of the background model

Possible inaccuracies in the SHERPA fast-simulation used for the background modelling studies can bias the obtained results. To keep this possibility under control and ensure that minor distortions can be absorbed within the flexibility of the chosen background functions, validation checks are performed by fitting such functions to the secondary POWHEG+ALPGEN FastSim samples and to a set of 8 experimental and 19 theoretical systematic variations, obtained from the nominal POWHEG+ALPGEN FastSim by varying different quantities during the generation process, such as the inner detector and muon system resolution, the muon momentum scale, the pile-up, the QCD scale and the value of the strong coupling parameter, and by using alternative PDF sets.

In each category, the spurious signal is evaluated for each of these alternative samples, the B-only goodness of fit is estimated on the nominal POWHEG+ALPGEN and the obtained results are compared to the ones provided by the baseline background selection procedure. As reported in table 4.19, the resulting SS is always stable in the nominal POWHEG+ALPGEN case and it passes the spurious signal test. Moreover, the background-only fits do not exhibit any significant mismodelling, having $P(\chi^2) \geq 1\%$.

The spurious signals measured for all the systematic variations are also stable, and satisfy the criteria highlighted in section 4.6.3 within the uncertainties. Additionally, they are compatible with the baseline SHERPA SS . This is shown in figure 4.11 for the ggF 1-jet Medium category, and similar results have been

Category	SS/dS [%]	SS	$P(\chi^2)_{\text{POWHEG+ALPGEN}}$
VBF Very High	-7.68	-0.79	0.08
VBF High	19.70	2.11	0.46
VBF Medium	1.45	1.23	0.64
VBF Low	0.00	1.18	0.43
ggF 2-jet Very High	9.02	8.49	0.78
ggF 2-jet High	14.90	-31.20	0.06
ggF 2-jet Medium	10.60	36.90	0.11
ggF 2-jet Low	8.06	36.90	0.26
ggF 1-jet Very High	10.90	8.09	0.49
ggF 1-jet High	13.10	22.90	0.21
ggF 1-jet Medium	-8.14	-37.50	0.86
ggF 1-jet Low	24.70	136.00	0.00
ggF 0-jet Very High	-4.91	19.00	0.39
ggF 0-jet High	20.10	66.00	0.05
ggF 0-jet Medium	6.76	52.40	0.09
ggF 0-jet Low	14.80	126.00	0.01

Table 4.19: Spurious signal and goodness of B-only fit results obtained using the baseline selected background models to fit the POWHEG-BOX+ALPGEN FastSim MC. The values reported for SS/dS include the MC statistical error.

obtained for all other categories. The flexibility of the chosen background models is therefore proven, especially when considering that the variation samples are not reweighted to the data sidebands, nor is their luminosity rescaled as is done in the nominal POWHEG+ALPGEN and baseline SHERPA cases.

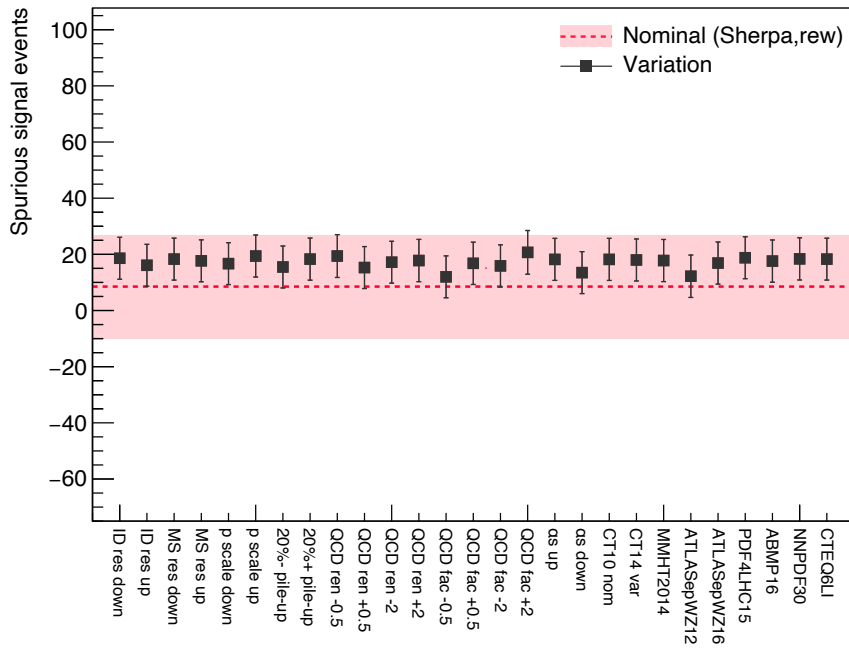


Figure 4.11: Values of SS (black points) obtained by fitting the baseline background model to each systematic variation sample, compared to the SS from the baseline SHERPA sample (dashed red line) and its fitted statistical error (red band). The shown category is ggF 1-jet Medium.

4.7 STATISTICAL TREATMENT

The $H \rightarrow \mu^+ \mu^-$ search aims at identifying a very rare process within the enormous volume of data provided by the LHC. As a consequence, the evaluation of the results and their interpretation lies in the realm of statistics, where the observed dataset is to be considered a random sample from an unknown population. Therefore, the potential presence of a signal must be assessed in terms of its statistical significance, incorporating all sources of uncertainty and providing a robust estimation that accounts for the occurrence of fluctuations.

The general strategy consists of defining a model, called likelihood function, that describes the measured data $\mathbf{D}$ in terms of a set of parameters $\mathbf{k} = \{k_1, \dots, k_m\}$ of unknown value, which contain all the relevant information about the underlying physics phenomenon. Determining the values of the parameters that best describe the data, in a process called parameter estimation, allows to make statistical inferences on the physical quantities that characterise an observation. The obtained results are then compared with the expectations, with the final goal of determining if the measurements are compatible with a given prediction, and at which level. Typically, these steps cannot be accomplished analytically given the number of parameters and the amount of data to process, and are instead performed with the aid of numerical calculation packages such as MINUIT [147], which is integrated in the ROOT [148] software and interfaced in the RooFIT [149] toolkit.

4.7.1 Model building

The likelihood function $L(\mathbf{D} | \mathbf{k})$ represents the probability of the observed data under a given hypothesis. It can be written as the probability density function (pdf) for the observed dataset $\mathbf{D}$, in terms of the parameters $\mathbf{k}$.

Two different types of parameters are included in the set $\mathbf{k}$: the parameters of interest (POIs) $\mu = \{\mu_1, \dots, \mu_n\}$, which correspond to the physical quantities that the analysis ultimately wants to measure, and the nuisance parameters (NPs) $\theta = \{\theta_1, \dots, \theta_m\}$, which provide additional variability to account for effects that are not perfectly known, at the expense of a higher uncertainty in the estimation of the POIs. In the $H \rightarrow \mu^+ \mu^-$ search, the chosen POI is the so-called combined signal strength μ_c , defined as the ratio of the observed signal yield in all the analysis categories, over its Standard Model expectation. The signal yield can be written as $S = \mathcal{L} A_H \sigma_H \text{BR}_{\mu^+ \mu^-}$, with $\mathcal{L}$ the integrated luminosity, A_H the signal acceptance of the detector, σ_H the production cross section of the Higgs boson and $\text{BR}_{\mu^+ \mu^-}$ its dimuon branching ratio. Therefore, the signal strength becomes

$$\mu_c = \frac{(\sigma_H \text{BR}_{\mu^+ \mu^-})_{\text{obs}}}{(\sigma_H \text{BR}_{\mu^+ \mu^-})_{\text{SM}}}, \quad (4.6)$$

such that $\mu_c = 0$ corresponds to zero observed signal events and $\mu_c = 1$ corresponds to the expected number of events according to the Standard Model.

The nuisance parameters considered in the $H \rightarrow \mu^+\mu^-$ analysis are the variables that characterise the background models, as well as the experimental and theoretical systematic uncertainties that affect the signal yield and distribution in the various categories. The theoretical uncertainties arise from the finite accuracy of the used simulated samples, and are related to the choice of the matrix element and parton shower generators, to the used PDF sets and to the applied QCD corrections. The experimental systematic uncertainties, on the other hand, are associated to the measurement process and concern the luminosity estimation, the pile-up, the trigger strategy and the reconstruction and identification of the physics objects used in the analysis. Both the theoretical and the experimental systematic uncertainties can be constrained using pre-existing knowledge coming from external, or subsidiary, measurements. They can be incorporated in the likelihood function as additional terms, which can be Gaussian or log-normal pdfs of the form $C_j(\tilde{\theta}_j | \theta_j, \Delta\theta_j)$, where $\tilde{\theta}_j$ is the value of the nuisance parameter θ_j obtained in the subsidiary measurement, and $\Delta\theta_j$ the uncertainty associated with such measurement.

The observed dataset consists of the $\mu^+\mu^-$ invariant mass spectra in all the analysis categories, organised in 500 bins of 0.1 GeV width, from 110 GeV to 160 GeV. Since all bins in all categories are statistically independent, the data $\mathbf{D}$ can be thought of as a set of individual measurements $n_{c,i}$, each corresponding to the number of dimuon events in the bin i of category c . The complete likelihood function can then be written as the product of the functions $L(n_{c,i} | \mu_c, \theta)$ for each $n_{c,i}$, multiplied by the subsidiary terms $C_j(\tilde{\theta}_j | \theta_j, \Delta\theta_j)$ for every nuisance parameter θ_j that has an associated external measurement:

$$L(\mathbf{D} | \mu_c, \theta) = \prod_c \prod_i L(n_{c,i} | \mu_c, \theta) \prod_j C_j(\tilde{\theta}_j | \theta_j, \Delta\theta_j). \quad (4.7)$$

Each $n_{c,i}$ follows a Poisson probability function [150] and thus

$$L(n_{c,i} | \mu_c, \theta) = \frac{\nu_{c,i}(\mu_c, \theta)^{n_{c,i}}}{n_{c,i}!} e^{-\nu_{c,i}(\mu_c, \theta)} \quad (4.8)$$

where $\nu_{c,i}$ is the expected rate, which is computed as

$$\nu_{c,i}(\mu_c, \theta) = \mu_c s_{c,i}(\theta) + ss_{c,i}(\theta) + b_{c,i}(\theta), \quad (4.9)$$

with $ss_{c,i}(\theta)$ the spurious signal yield, and $s_{c,i}(\theta)$ and $b_{c,i}(\theta)$ the expected signal and background yields in bin i of category c , obtained by integrating in a given bin the signal model S_c^{pdf} and the background model B_c^{pdf} described in section 4.5 and section 4.6 respectively:

$$\begin{aligned} s_{c,i}(\theta) &= \sum_p s_{c,p} \int_i S_c^{\text{pdf}}(m_{\mu^+\mu^-} | \theta_{c,s}) dm_{\mu^+\mu^-} \\ b_{c,i}(\theta) &= b_c \int_i B_c^{\text{pdf}}(m_{\mu^+\mu^-} | \theta_{c,b}) dm_{\mu^+\mu^-} \\ ss_{c,i}(\theta) &= ss_c \int_i S_c^{\text{pdf}}(m_{\mu^+\mu^-} | \theta_{c,s}) dm_{\mu^+\mu^-}, \end{aligned} \quad (4.10)$$

where the index p runs over the considered production modes ggF , VBF , VH and $t\bar{t}H$, and $\theta_{c,s}$ and $\theta_{c,b}$ are the nuisance parameters related to the signal and the background respectively. Finally, ss_c is the total number of spurious signal events in category c , corresponding to the value of SS extracted in section 4.6.3, and $s_{c,p}$, b_c are the expected numbers of signal and background events respectively. The former is calculated separately for each production mode and fixed to the value predicted by the signal model, and the latter is an adjustable nuisance parameter that must be determined from the data.

4.7.2 Statistical inference

When $\mathbf{D}$ is fixed as a result of an experimental measurement, the global maximum of $L(\mathbf{D} | \mathbf{k})$ corresponds to the values of the parameters $\mathbf{k}$ for which the observed dataset is most probable. Therefore, parameter estimation consists of maximising the likelihood function or, equivalently, minimising the negative logarithm of the likelihood function $-\ln L(\mathbf{D} | \mathbf{k})$, which is computationally easier as it involves summations instead of multiplications of the contributing terms. In practice, this translates into finding the solutions to the equations

$$\frac{\partial \ln L(\mathbf{D} | \mathbf{k})}{\partial k_j} = 0 \quad \forall k_j \text{ in } \mathbf{k}, \quad (4.11)$$

where the procedures followed to calculate the parameter values are called maximum-likelihood estimators (MLEs) and denoted with the symbol $\hat{\mathbf{k}}$ [151].

In the $H \rightarrow \mu^+ \mu^-$ analysis, the complete log-likelihood function $-\ln L(\mathbf{D} | \mu_c, \theta)$ is minimised simultaneously in the twenty analysis categories, providing the MLE for the nuisance parameters and for the combined signal strength μ_c . The obtained estimates acquire scientific meaning if they are associated to their respective uncertainties. The goal is to make a statement on the compatibility of the observed data with a hypothesis H_{μ_c} , characterised by the signal strength μ_c . This is accomplished by first defining a variable called the test statistic, t_{μ_c} , which condenses the discriminating power of the full measurement described by the likelihood function $L(\mathbf{D} | \mathbf{k})$ into a single number:

$$t_{\mu_c} = -2 \ln \lambda(\mu_c) = -2 \ln \frac{L(\mathbf{D} | \mu_c, \hat{\theta}(\mu_c))}{L(\mathbf{D} | \hat{\mu}_c, \hat{\theta})}, \quad (4.12)$$

where $\lambda(\mu_c)$, called profile likelihood ratio, is the ratio of two likelihood functions. The numerator, $L(\mathbf{D} | \mu_c, \hat{\theta})$, is a conditional likelihood function and represents the signal strength μ_c hypothesis being tested, in which the nuisance parameters assume the MLE values $\hat{\theta}(\mu_c)$ obtained with μ_c fixed to its hypothesised value. The denominator $L(\mathbf{D} | \hat{\mu}_c, \hat{\theta})$, instead, is the unconditional likelihood function and has all its parameters set to their MLE values, to represent the hypothesis corresponding to the signal strength that best describes the observed data. The test statistic orders all the possible outcomes, or datasets $\mathbf{D}$, in terms of how much

signal they would contain. Under the hypothesis H_{μ_c} , the probability to obtain data containing as much signal as the observations, or more, can then be calculated by integrating the distribution of the test statistic $g(t_{\mu_c} | \mu_c)$ as

$$p_{\mu_c} = \int_{t_{\mu_c}^{\text{obs}}}^{\infty} g(t_{\mu_c} | \mu_c) dt_{\mu_c} , \quad (4.13)$$

which is known as the p -value and is the probability that the tested hypothesis would produce data with t_{μ_c} equal or larger than the observed value $t_{\mu_c}^{\text{obs}}$. The lower the p -value, the less is the compatibility of the data with a given hypothesis.

In the $H \rightarrow \mu^+ \mu^-$ study, hypothesis testing proceeds through proof by contradiction. This means that, when performing a search for a given phenomenon, the aim is to reject the hypothesis without that phenomenon with enough confidence such that the probability that the observed dataset was due to the presence of a signal is sufficiently high. This translates into requiring that the observed p -value for H_0 , or p_b , is below a specified threshold, which is commonly chosen as $p_b^{\text{obs}} = 2.87 \times 10^{-7}$ when claiming the observation of a signal. Usually, the p -value is converted into an equivalent statistical significance Z , which corresponds to the quantile² Φ^{-1} of the standard Gaussian as a function of $1 - p$

$$Z = \Phi^{-1}(1 - p) , \quad (4.14)$$

such that a Gaussian-distributed variable found Z standard deviations above its mean has an upper-tail probability equal to p . The significance corresponding to p_b^{obs} is $Z^{\text{obs}} = 5$ standard deviations, or 5σ . It is also useful to compare the observed Z value with the significance expected under the assumption of a given hypothesis, which quantifies the sensitivity of an experiment. This can be estimated as the median significance of an ensemble of measurements performed under the same conditions, but in practice the ensemble is typically replaced by a single representative dataset called the Asimov dataset [152], which corresponds to the median expected data with no fluctuations, such that the MLE of all the parameters are the values generated under the given hypothesis.

The inability to reject the background-only hypothesis with sufficient certainty, meaning that the observed significance is below the needed threshold, does not automatically translate into the exclusion of a signal. In fact, it is still possible to find a range $[0, \mu_c^{\text{up}}]$ of μ_c values for which the signal-plus-background assumption cannot be rejected on the basis of the available observations. Such range is determined in the so-called limit setting procedure. It performs a scan of the possible μ_c values to find the largest one, denoted as the upper limit μ_c^{up} , for which the compatibility with the signal-plus-background hypothesis is equal or higher than a given threshold. This threshold is typically chosen as 5% in high-energy particle physics searches, and all values of the signal strength above μ_c^{up} are then said to be excluded with a level of confidence $\text{CL} = 1 - 5\% = 95\%$. According to a

² A quantile is the inverse of the cumulative distribution.

prescription known as the CL_s method [153], the compatibility is quantified using a modified version of the p -value,

$$CL_s = \frac{p_{s+b}}{p_b}, \quad (4.15)$$

which is the ratio of p_{s+b} , corresponding to the probability of the observed data under the signal-plus-background hypothesis, to p_b , which assumes the background-only hypothesis. Such definition prevents the exclusion of a signal in the presence of downwards fluctuations of the background, counterbalancing them with the decreasing denominator. In other words, if the observed data is very improbable under both the aforementioned hypotheses, it will not be used to reject the signal-plus-background one. The effect of this intervention is that the limit setting will never produce an empty interval, even for large deficits of event counts in the signal region, because a small region that is reported to be not excluded at the stated confidence level always remains. The p -values in the numerator and denominator of CL_s are calculated using the test statistic

$$q_{\mu_c} = \begin{cases} -2 \ln \frac{L(\mathbf{D} | \mu_c, \hat{\theta}(\mu_c))}{L(\mathbf{D} | \hat{\mu}_c, \hat{\theta})} & 0 \leq \hat{\mu}_c \leq \mu_c \\ 0 & \hat{\mu}_c > \mu_c \end{cases}, \quad (4.16)$$

where $\hat{\theta}(\mu_c)$ are the values of the nuisance parameters that maximise the conditional likelihood function with μ_c fixed to a hypothesised value. The MLE of the signal strength must be in the range $0 \leq \hat{\mu}_c \leq \mu_c$ to provide useful information about the incompatibility between the data and the hypothesis. In fact, if $\hat{\mu}_c > \mu_c$ the observations cannot constitute evidence against it. To avoid that these are nevertheless interpreted as such, they are explicitly considered to be maximally consistent with the hypothesis, giving $q_{\mu_c} = 0$. This prevents the exclusion of a signal due to upwards fluctuations.

It is also useful to evaluate the expected upper limits, corresponding to the median outcomes under given hypotheses. These are obtained using the Asimov dataset, determining the asymptotic test statistic $q_{\mu_c, A}$ and computing the value of the signal strength for which the median CL_s is equal to 5%.

4.8 RESULTS

The results of the combined maximum-likelihood $S + B$ fit are presented in figure 4.12, which shows the invariant mass spectra of the $\mu^+\mu^-$ pair in all analysis categories. Additionally, the signal-plus-background fitted distributions for each category singularly are presented in figure 4.14 and the data, background and signal yields measured in the 120 – 130 GeV region are listed in table 4.20.

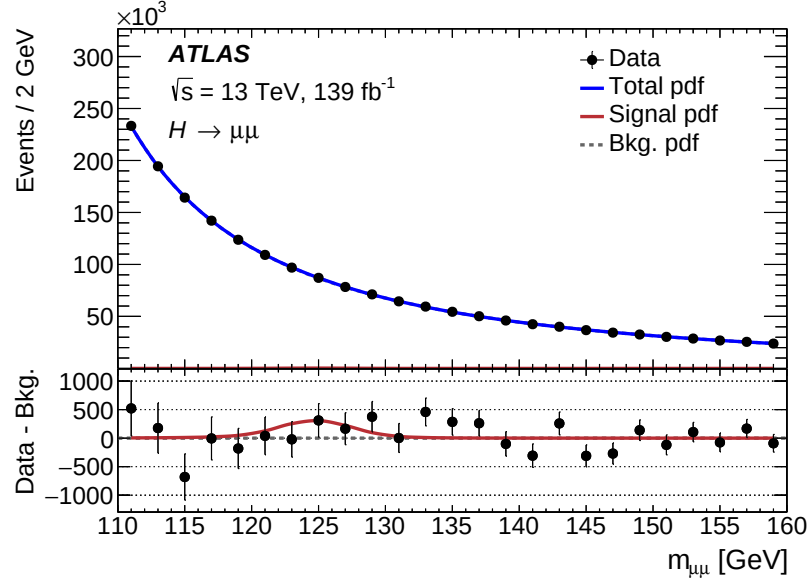
The obtained best-fit value of the signal strength parameter is $\mu_c = 1.2 \pm 0.6$, corresponding to an observed significance of 2.0 standard deviations, and the expected significance with respect to the background-only hypothesis is equal to 1.7 standard deviations. The ten leading systematic uncertainties that affect the

Category	Data	S_{SM}	S	B	$\frac{S_{SM}}{\sqrt{B}}$	$\frac{S}{B}$ [%]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2
ggF 2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0
ggF 2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0
ggF 2-jet Medium	18311	79 ± 15	90 ± 50	18320 ± 90	0.66	0.5
ggF 2-jet Low	36409	63 ± 17	70 ± 40	36340 ± 140	0.37	0.2
ggF 1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8
ggF 1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9
ggF 1-jet Medium	24576	90 ± 11	100 ± 50	24290 ± 100	0.67	0.4
ggF 1-jet Low	73459	125 ± 17	150 ± 70	73480 ± 190	0.53	0.2
ggF 0-jet Very High	15986	59 ± 11	70 ± 40	16090 ± 90	0.55	0.4
ggF 0-jet High	46523	99 ± 13	120 ± 60	46190 ± 150	0.54	0.3
ggF 0-jet Medium	91392	119 ± 14	140 ± 70	91310 ± 210	0.46	0.2
ggF 0-jet Low	121354	79 ± 10	90 ± 50	121310 ± 280	0.26	0.1
VH – 4ℓ	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6
VH – 3ℓ High	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2
VH – 3ℓ Medium	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2

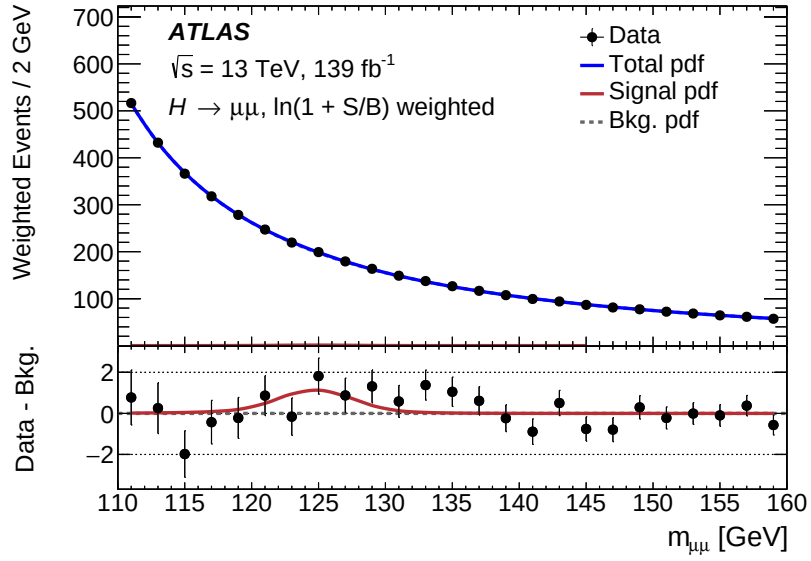
Table 4.20: From left to right: number of data events observed in the signal region, number of signal events predicted by the Standard Model, number of signal and background events derived from the combined fit to the data, measured number of signal events divided by the square root of the background, and signal-to-background ratio, for each analysis category.

signal strength, ordered by their impact, are presented in figure 4.13, where those with less than 0.5% magnitude are not shown for simplicity.

In the absence of a direct observation, the observed upper limit on the signal strength at 95% CL is found to be 2.2, with an expected limit of 1.1 under the assumption of no $H \rightarrow \mu^+ \mu^-$ signal and of 2.0 under the SM $H \rightarrow \mu^+ \mu^-$ hypothesis. The corresponding observed upper limit on the $H \rightarrow \mu^+ \mu^-$ branching ratio at 95% CL is $BR(H \rightarrow \mu^+ \mu^-) < 4.7 \times 10^{-4}$, assuming the SM Higgs boson production cross section. These results represent an improvement of a factor 2.5 in expected sensitivity with respect to the previous ATLAS publication, of which about 75% depends on the reduction of the statistical uncertainty brought by the larger analysed dataset, and the additional 25% can be attributed to the more advanced analysis techniques employed and presented in this thesis.



A



B

Figure 4.12: Observed dimuon invariant mass spectra in all the analysis categories, where the data points are shown in black and the blue line is the fitted $S + B$ model. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A) shows the unweighted events, and (B) the events weighted by $\ln(1 + S/B)$, where S and B are the observed signal and background yields. The error bars represent the statistical uncertainties.

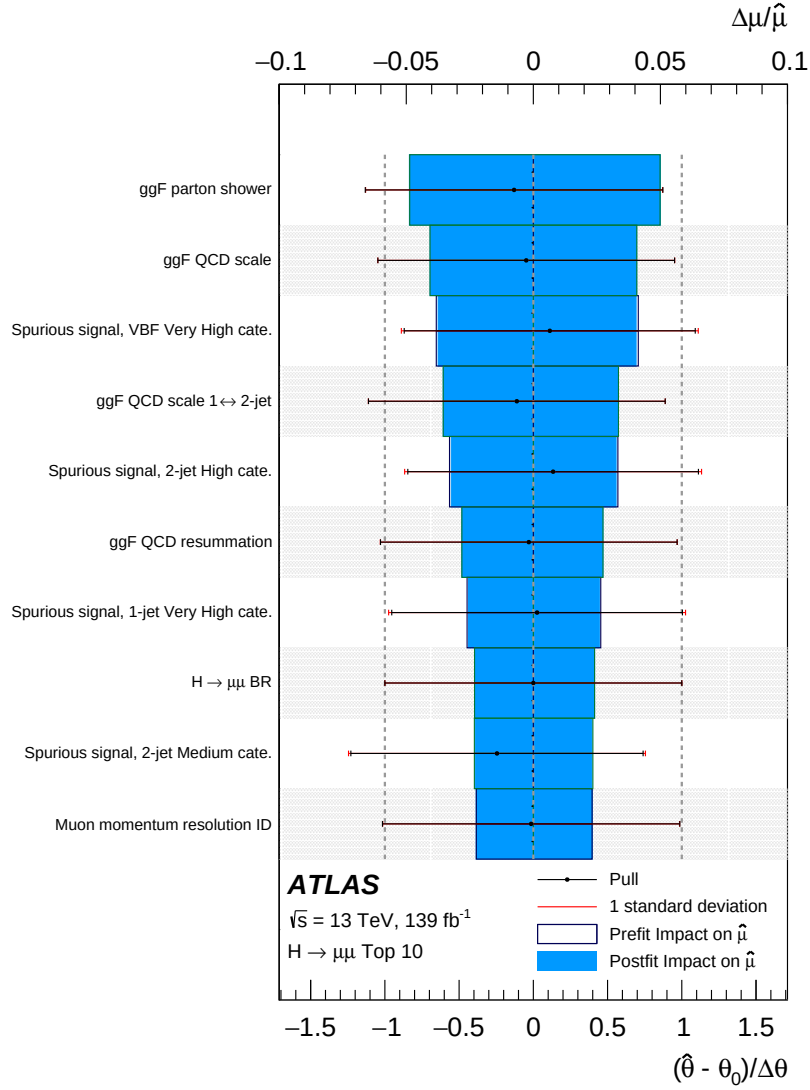


Figure 4.13: Leading systematic uncertainties, ordered by their impact on the signal strength. The coloured bands, as a function of the upper x-axis, show the relative impact, computed by comparing the nominal $\hat{\mu}_c$ value to the one obtained when fixing the corresponding NP θ_m to its MLE value $\hat{\theta}_m$, plus-or-minus its uncertainty, blue for the post-fit and white for the pre-fit. The black points, as a function of the lower x-axis, show the deviation of the fitted nuisance parameters $\hat{\theta}_m$ from their nominal values, and the red points correspond to one standard deviation.

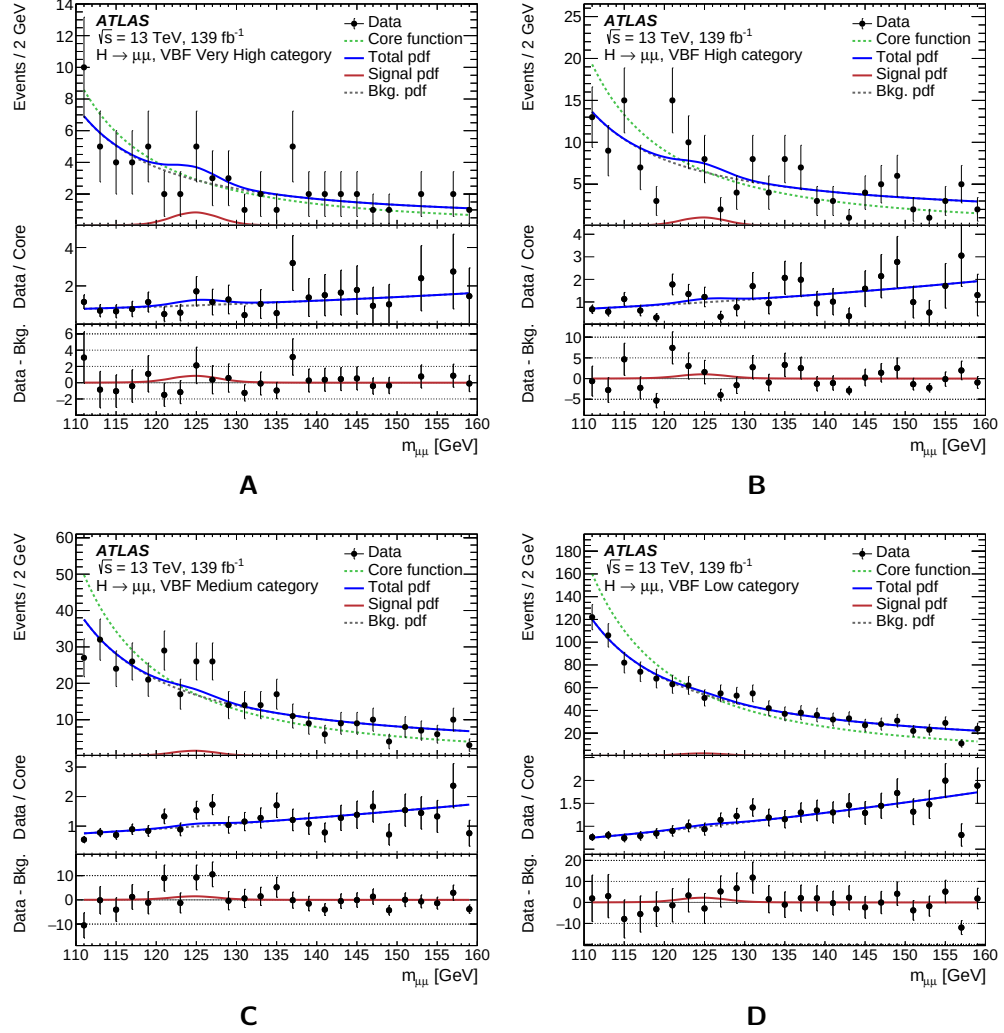


Figure 4.14: Observed dimuon invariant mass spectra. The data points are shown in black, where the error bars represent the statistical uncertainties. The blue line is the fitted $S + B$ model, the red line is the signal model and the green dashed line is the core function. The middle panel shows the ratio between the data and the background model, both divided by the core component. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A)-(D) are VBF Very High, High, Medium and Low categories, (E)-(H) are ggF 2-jet Very High, High, Medium and Low categories, (I)-(L) are ggF 1-jet Very High, High, Medium and Low categories, (M)-(P) are ggF 0-jet Very High, High, Medium and Low categories, (Q)-(T) are the $VH - 4\ell$, $VH - 3\ell$ High, $VH - 3\ell$ Medium and $t\bar{t}H$ categories.

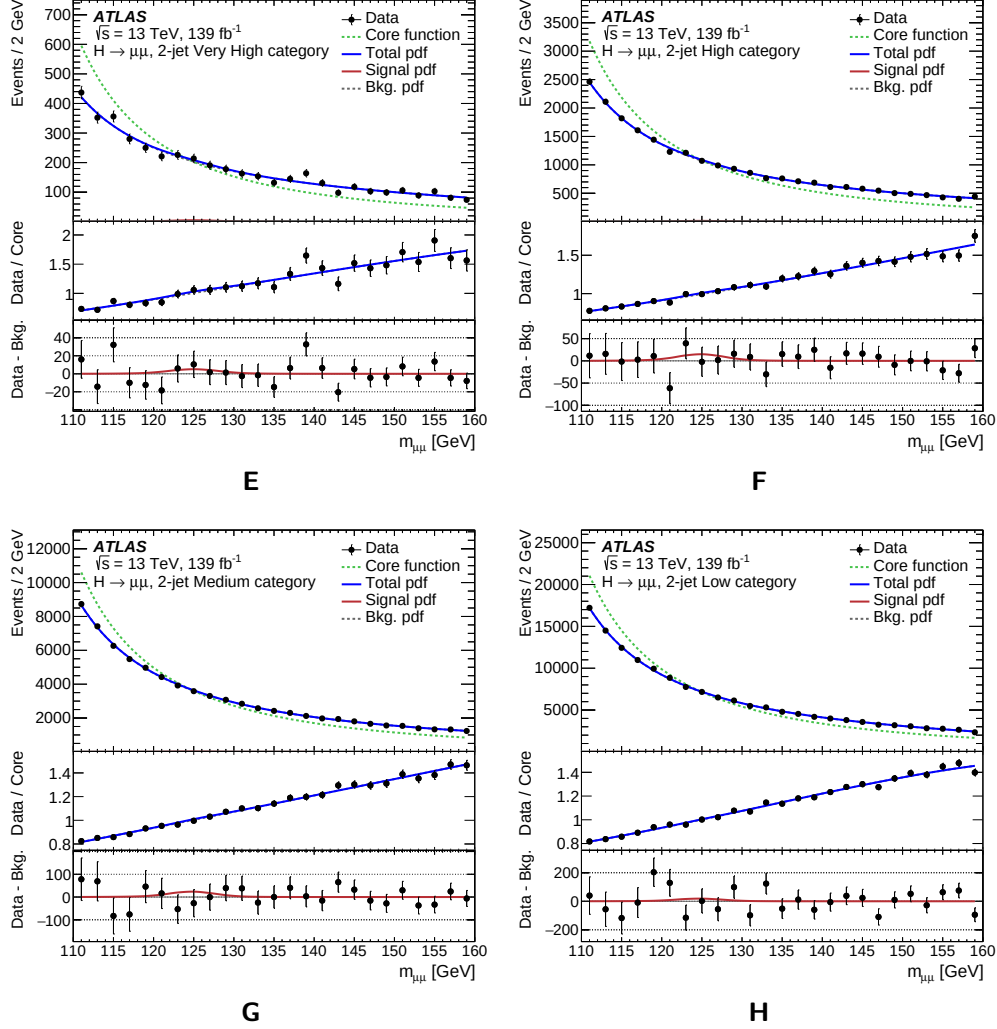


Figure 4.14: Observed dimuon invariant mass spectra. The data points are shown in black, where the error bars represent the statistical uncertainties. The blue line is the fitted $S + B$ model, the red line is the signal model and the green dashed line is the core function. The middle panel shows the ratio between the data and the background model, both divided by the core component. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A)-(D) are VBF Very High, High, Medium and Low categories, (E)-(H) are ggF 2-jet Very High, High, Medium and Low categories, (I)-(L) are ggF 1-jet Very High, High, Medium and Low categories, (M)-(P) are ggF 0-jet Very High, High, Medium and Low categories, (Q)-(T) are the $VH - 4\ell$, $VH - 3\ell$ High, $VH - 3\ell$ Medium and $t\bar{t}H$ categories.

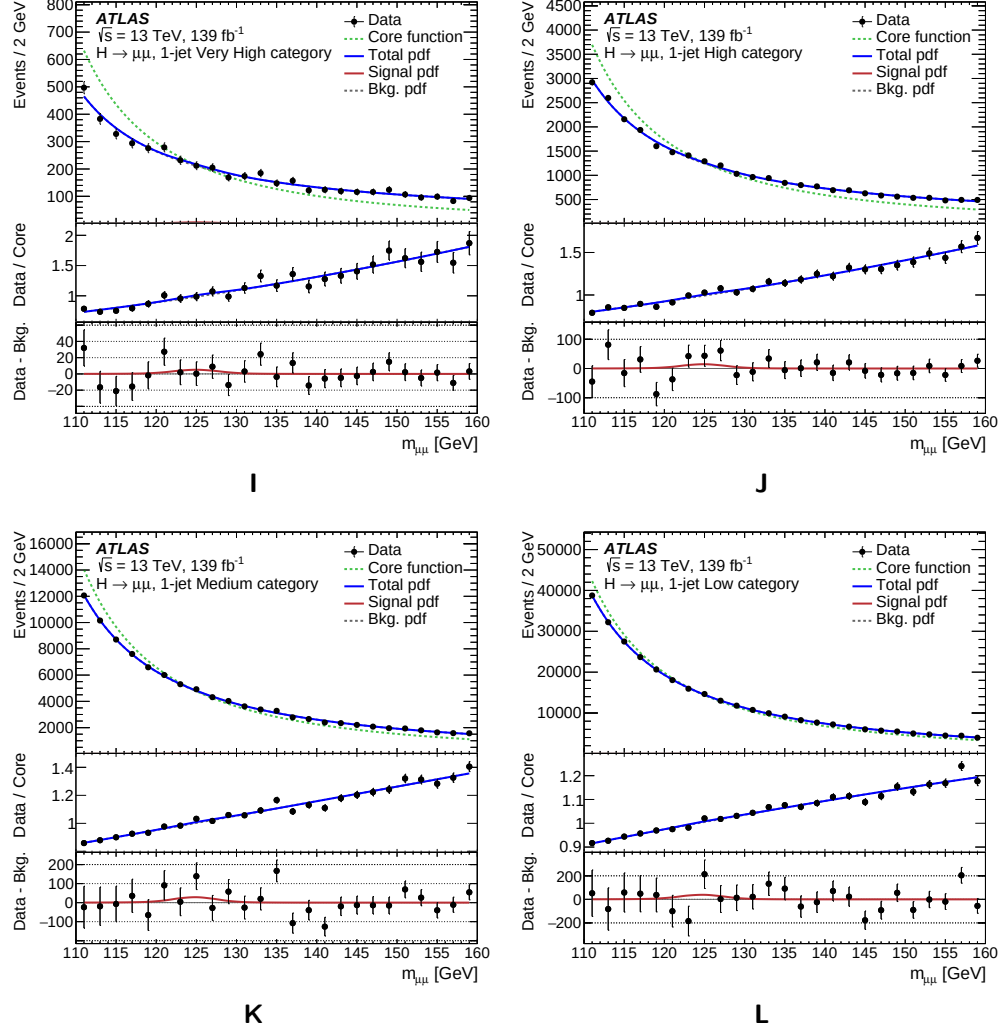


Figure 4.14: Observed dimuon invariant mass spectra. The data points are shown in black, where the error bars represent the statistical uncertainties. The blue line is the fitted $S + B$ model, the red line is the signal model and the green dashed line is the core function. The middle panel shows the ratio between the data and the background model, both divided by the core component. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A)-(D) are VBF Very High, High, Medium and Low categories, (E)-(H) are ggF 2-jet Very High, High, Medium and Low categories, (I)-(L) are ggF 1-jet Very High, High, Medium and Low categories, (M)-(P) are ggF 0-jet Very High, High, Medium and Low categories, (Q)-(T) are the $VH - 4\ell$, $VH - 3\ell$ High, $VH - 3\ell$ Medium and $t\bar{t}H$ categories.

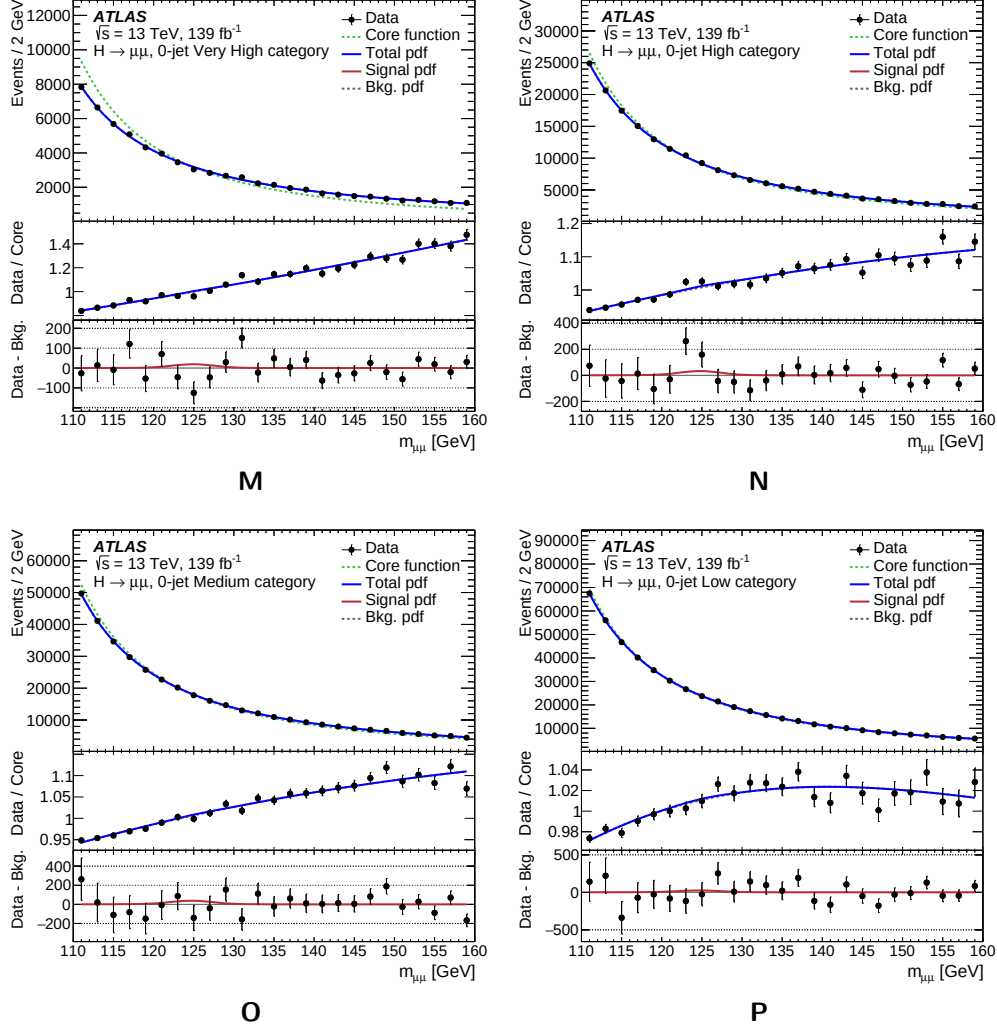


Figure 4.14: Observed dimuon invariant mass spectra. The data points are shown in black, where the error bars represent the statistical uncertainties. The blue line is the fitted $S + B$ model, the red line is the signal model and the green dashed line is the core function. The middle panel shows the ratio between the data and the background model, both divided by the core component. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A)-(D) are VBF Very High, High, Medium and Low categories, (E)-(H) are ggF 2-jet Very High, High, Medium and Low categories, (I)-(L) are ggF 1-jet Very High, High, Medium and Low categories, (M)-(P) are ggF 0-jet Very High, High, Medium and Low categories, (Q)-(T) are the $VH - 4\ell$, $VH - 3\ell$ High, $VH - 3\ell$ Medium and $t\bar{t}H$ categories.

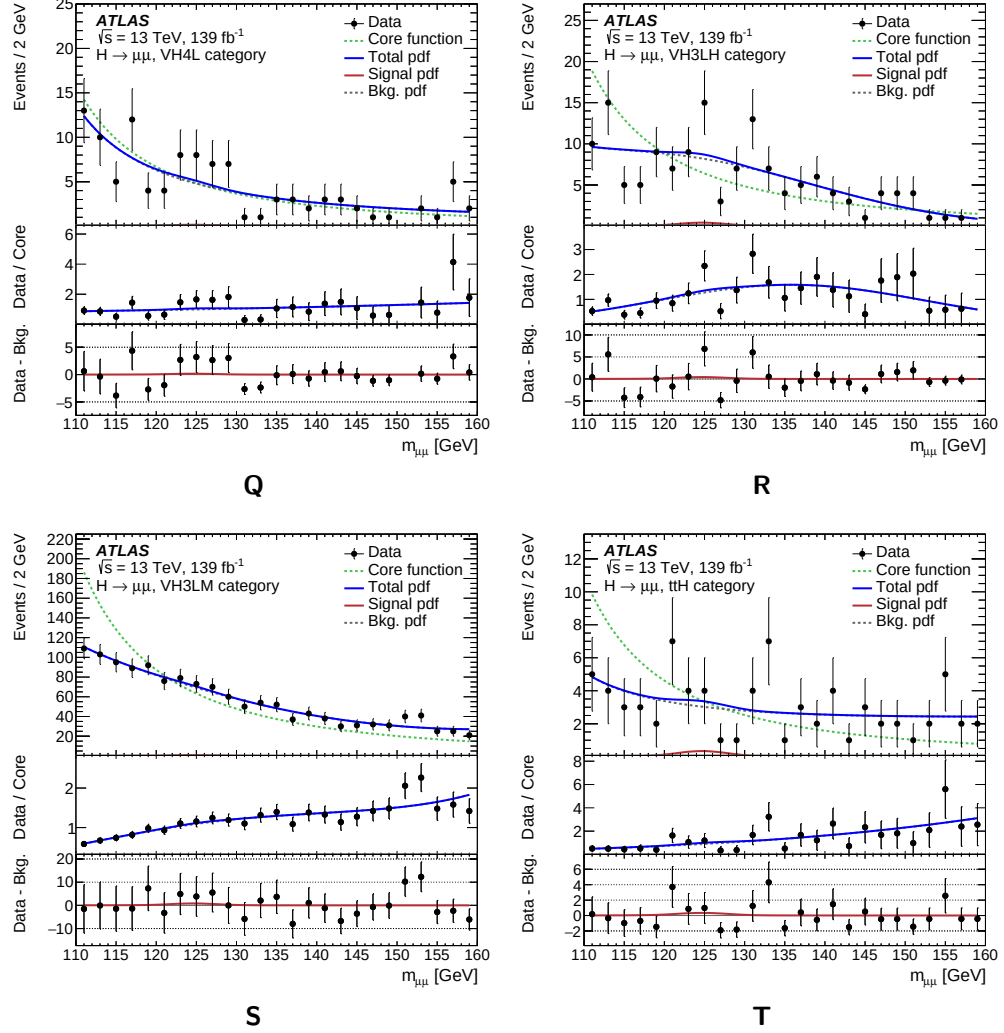


Figure 4.14: Observed dimuon invariant mass spectra. The data points are shown in black, where the error bars represent the statistical uncertainties. The blue line is the fitted $S + B$ model, the red line is the signal model and the green dashed line is the core function. The middle panel shows the ratio between the data and the background model, both divided by the core component. The bottom panel compares the signal model, normalised to the signal best-fit value, to the difference between the data and the background model. (A)-(D) are VBF Very High, High, Medium and Low categories, (E)-(H) are ggF 2-jet Very High, High, Medium and Low categories, (I)-(L) are ggF 1-jet Very High, High, Medium and Low categories, (M)-(P) are ggF 0-jet Very High, High, Medium and Low categories, (Q)-(T) are the $VH - 4\ell$, $VH - 3\ell$ High, $VH - 3\ell$ Medium and $t\bar{t}H$ categories.

CONCLUSION AND OUTLOOK

The $H \rightarrow \mu^+ \mu^-$ search discussed in this thesis contributes vastly to the current, most advanced knowledge about the Higgs boson's interactions with fermions, and in particular with fermions of the second generation. In fact, despite not leading to a direct observation of this decay, the obtained results can be interpreted in terms of the Higgs coupling strength to muons, providing its most precise measurement. This can be compared to the Standard Model's expectations, to gain insights about the mass generation mechanism. Additionally, the strategy and the achievements of the Run 2 ATLAS analyses can be used as inputs to perform sensitivity projections, which quantify the future experimental reach.

The interactions of the Higgs boson can be studied within the so-called κ framework, described in detail in [154]. Its basic idea is to introduce a set of parameters, called coupling strength modifiers, that represent the deviations of the measurements from the Standard Model. As a result, the observed coupling strengths can be written as

$$y_V = \sqrt{\kappa_V} \frac{m_V}{v} \quad (5.1)$$

for weak gauge bosons $V = Z, W^\pm$ of mass m_V , and as

$$y_\psi = \kappa_\psi \frac{m_\psi}{v} \quad (5.2)$$

for fermions ψ of mass m_ψ , where v is the vacuum expectation value of the Higgs field introduced in section 1.1.1. The coupling strength modifiers κ_ψ and κ_V can be estimated from measurements of the signal strength, being equal to 1 when the observations correspond to the Standard Model.

The values of y_V and y_ψ obtained by ATLAS in Run 2 are shown in figure 5.1 as a function of the mass of the interacting fermions and bosons, and compared to the SM expectations. All interactions presented have been experimentally observed, with the exception of the one between the Higgs boson and muons, for which the tiny decay branching ratio also reflects in the size of the reported statistical uncertainty on $y_{\psi=\mu}$. However, its spread is already reduced by a factor

5 when compared to the previous Run 1 measurements from ATLAS and CMS combined [155]. It strongly hints towards the existence of a coupling between muons and the Higgs boson, and it is bound to become consistently smaller when increasing the amount of studied data, giving more precise information on the compatibility with the Standard Model.

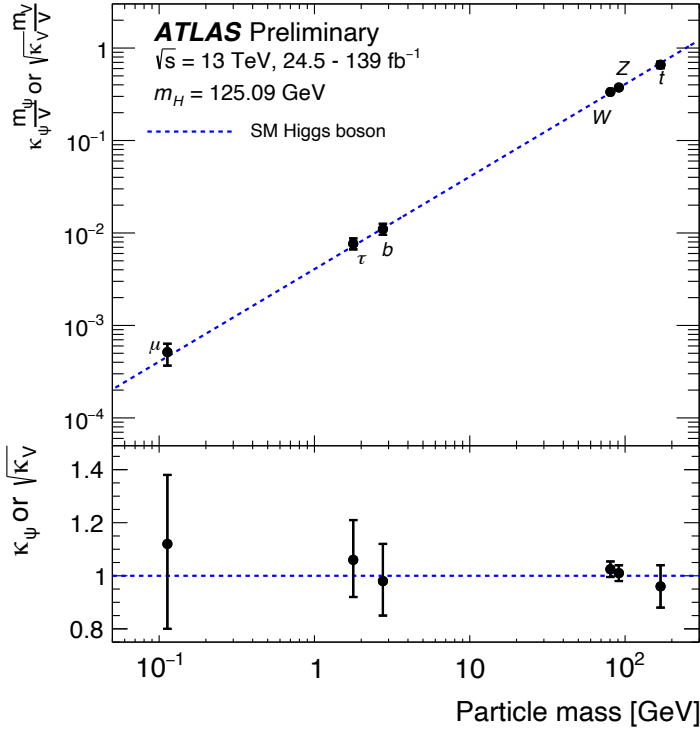


Figure 5.1: Coupling strengths of the Standard Model Higgs boson as a function of the mass of the particles with which it interacts, evaluated using the full Run 2 data and compared to the Standard Model expectations (blue dashed line). The bottom pad shows the values normalised to the SM expectations [156].

In fact the sensitivity to the $H \rightarrow \mu^+ \mu^-$ decay, with its small number of expected signal events and relatively clean final state, is dominated by statistical uncertainties. In this respect, the future of this search is bright, since the larger datasets that will characterise the next data-taking periods can bring major improvements. As discussed in section 2.1.1, the LHC will deliver more than 3000 fb^{-1} during its high-luminosity programme, at a centre-of-mass energy of 14 TeV. Its achievable experimental reach can be assessed by performing extrapolations of the current state-of-the-art analyses to the foreseen future conditions. This can be done thoroughly by scaling the luminosity values, simulating a higher pile-up and increasing the production cross sections in accordance to the expected centre-of-mass energy, while accounting for the predicted changes in the performance of the detectors and of the offline reconstruction and identification procedures. However, a number of assumptions must be made when formulating predictions.

Scenario	$\Delta\mu_c$	$(\Delta\mu_c)_{\text{stat}}$	$(\Delta\mu_c)_{\text{exp}}$	$(\Delta\mu_c)_{\text{theor}}$
Run 2 (79.8 fb ⁻¹)	+1.04 -1.06	+0.99 -1.03	+0.03 -0.03	+0.32 -0.27
HL-LHC (3000 fb ⁻¹)	+0.15 -0.14	+0.12 -0.13	+0.03 -0.03	+0.08 -0.05

Table 5.1: Signal strength precision for the $H \rightarrow \mu^+\mu^-$ decay channel, as estimated with the first 79.8 fb⁻¹ of Run 2 and in the HL-LHC scenario, and decomposed in its statistical, experimental and theoretical components [157].

A typical studied HL-LHC scenario considers the luminosity uncertainty to be 1%, and assumes that the increasing pile-up will be compensated by improvements in the detector systems. Under these considerations, the achievable precision on the signal strength μ_c is estimated as the ratio of the total uncertainty on the signal yield to that expected from the SM, $\Delta\mu_c = \Delta S/\Delta S_{\text{SM}}$. Its value, as well as its decomposition in terms of the statistical, experimental and theoretical components, is shown in table 5.1. The calculations assume that most systematic uncertainties remain unchanged with respect to Run 2. However, the leading background modelling uncertainty depends on the amount of available data, and becomes negligible in the HL-LHC scenario. This drives an overall reduction of the systematic effects, such that the $H \rightarrow \mu^+\mu^-$ analysis will still be limited by statistical uncertainties even in the high-luminosity phase.

Estimates of the coupling strengths calculated within the same scenario are shown in figure 5.2. Here, thanks to the increased dataset, the uncertainty on κ_μ will reach levels comparable to other κ_ψ , which scale much larger coupling strengths such as the one to bottom quarks. Additionally, projections based on generator-level simulated samples allow to estimate the significance expected at the end of the HL-LHC. This is reported to be larger than 9σ , well above the standard threshold needed to claim an observation [158].

Nevertheless, all these studies are based on the previous $H \rightarrow \mu^+\mu^-$ analysis strategy, which was applied only to the first 79.8 fb⁻¹ of Run 2. All the important improvements presented in this thesis, such as the refined categorisation and the advanced background modelling that account for 25% enhanced sensitivity, were not taken into account. It is therefore worth evaluating an additional simplified projection, which extrapolates the full Run 2 results discussed in this thesis and estimates that 5σ will be reached with about 1300 fb⁻¹. The calculation is performed under the assumption that the significance and the uncertainty on the signal strength scale purely with the luminosity as $1/\sqrt{\mathcal{L}}$, while effects such as increases of the pile-up and systematic uncertainties are not taken into account. This is reasonable as long as the statistical uncertainty can be considered to be dominant, and offers a fair indication that $H \rightarrow \mu^+\mu^-$ could be observed with ATLAS at the beginning of the HL-LHC phase.

In concomitance with the results discussed in this thesis, the CMS collaboration published the $H \rightarrow \mu^+\mu^-$ analysis it performed on the full Run 2 data [159]. While ATLAS achieved an observed and expected significance of 2.0 and 1.7 standard deviations respectively, CMS reported evidence for this decay, corresponding to an

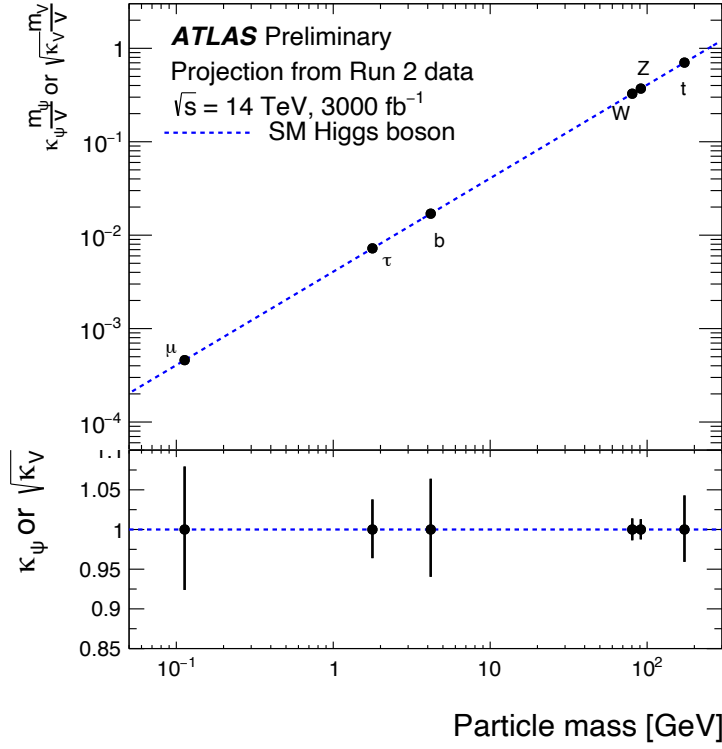


Figure 5.2: HL-LHC projections for the coupling strengths of the Standard Model Higgs boson as a function of the mass of the particles with which it interacts, extrapolated from the 79.8 fb^{-1} Run 2 analysis and compared to the Standard Model expectations (blue dashed line). The bottom pad shows the values normalised to the SM expectations [157].

observed significance of 3.0σ , where the expectation for a SM Higgs boson is 2.5σ . When compared to ATLAS, the CMS detector benefits from a stronger magnetic field, which provides a dimuon resolution that is about 2.2 times better. This, in turn, accounts for the main difference in sensitivity between the two experiments when searching for dimuon decays.

In summary, at the horizon of its experimental observation, the $H \rightarrow \mu^+\mu^-$ decay plays a role of major importance in the field of high-energy particle physics, and a growing interest is brought to its study. The work presented in this thesis contributes to laying the foundations for the future developments of this search, from which a better understanding of the Higgs boson and of the fermion mass generation mechanism can be achieved. This, in turn, will shed new light on the remaining unprobed parts of the Standard Model.

LIST OF SYMBOLS

A_μ	Generic gauge field
B_μ	Electroweak $U(1)_Y$ gauge field
B^{pdf}	Background model
b	Bottom quark
B	Background yield
C	Colour charge
$\mathcal{CB}$	Double-sided Crystal Ball distribution
c	Charm quark
d_0	Transverse impact parameter
dS	Error on signal yield
$\mathbf{D}$	Generic dataset
$\mathcal{D}_\mu$	Gauge-covariant four-vector derivative
d	Down quark
DY_{LS}	Drell-Yan lineshape
e	Electron
E_p	Energy of a particle p
e	Euler number
$\mathcal{F}$	Geometric luminosity reduction factor
f_{rev}	LHC revolution frequency
f^{abc}	Antisymmetric group structure constants
$F_{\mu\nu}^a$	Field strength tensor
F_c	Core background function
F_ε	Empirical background function
$f(x_j, Q^2)$	Parton distribution function
g	Gluon
$\mathcal{G}$	Gaussian distribution
G_F	Fermi constant
h	Physical Higgs field
H	Higgs boson
H_{μ_c}	Hypothesis characterised by signal strength μ_c
i	Imaginary unit

$\mathbf{k}$	Vector of likelihood function parameters
$\hat{\mathbf{k}}$	Vector of maximum-likelihood estimators for the parameters $\mathbf{k}$
$\mathcal{L}$	Lagrangian density
ℓ	Generic charged lepton (e or μ)
$L(\mathbf{D} \mathbf{k})$	Likelihood function
L	Instantaneous luminosity
$\mathcal{L}$	Integrated luminosity
m_K	Mass of generic object K
m_H	Mass of the Higgs boson
$m_{\mu^+\mu^-}$	Dimuon invariant mass
n_b	Number of bunches in a beam
N_p	Number of particles per bunch
$n_{c,i}$	Number of dimuon events in bin i of category c
$\mathcal{O}_K$	BDT score for process K
$\mathbf{p}$	Momentum vector
$P(\chi^2)$	Chi-square probability
p	Proton
$\mathbf{p}_T$	Transverse momentum
p_T	Magnitude of transverse momentum
p_T^L	Magnitude of transverse momentum of leading muon
p_T^S	Magnitude of transverse momentum of subleading muon
$\cancel{p}_T$	Missing transverse momentum
$\cancel{p}_T$	Magnitude of missing transverse momentum
p	p-value
p_x	Momentum component along the x-axis
p_y	Momentum component along the y-axis
p_z	Momentum component along the beam axis
Q	Electric charge
q_{μ_c}	Test statistic used in $H \rightarrow \mu^+\mu^-$ limit setting
Q	Momentum transfer
q	Generic quark
$\bar{q}$	Generic antiquark
r	Radial coordinate
$\mathcal{R}$	Generic resonance
R_p	Size of cone for the anti- k_t algorithm
$\sqrt{s}$	Centre-of-mass energy of a proton-proton collision
$\sqrt{\hat{s}}$	Centre-of-mass energy of a hard scattering

S^{pdf}	Signal model
s	Strange quark
SS	Spurious signal systematic uncertainty
S	Signal yield
T^a	Group generator matrices
T	Weak isospin
t	Time variable
$t_{\mu c}$	Test statistic
t	Top quark
U	Local gauge transformation
u	Up quark
v	Physical Higgs vacuum expectation value
$V(\phi)$	Higgs potential
V_μ	Generic weak boson field
V	Generic weak boson
V^*	Off-shell generic weak gauge boson
$W^\pm$	Charged weak gauge bosons
$W_\mu^{a=1,2,3}$	Electroweak $SU(2)_L$ gauge fields
$W_\mu^\pm$	Charged weak gauge fields
x_j	Bjorken-Feynman scaling variable for parton j
x_μ	Four-vector of space-time coordinates
Y	Weak hypercharge
y	Rapidity
y_ψ	Yukawa coupling strength for fermion ψ
Z	Neutral weak gauge boson
z_0	Longitudinal impact parameter
Z_μ	Neutral weak gauge field
Z	Significance
α_C	Strong coupling parameter
α_L	$U(1)_L$ coupling parameter
α_Y	$SU(2)_Y$ coupling parameter
β^*	Betatron function at the interaction point
γ_p	Relativistic Lorentz factor for protons
γ	Photon
γ^μ	Dirac gamma-matrices
γ_μ	Electromagnetic, or photon, gauge field
$\Gamma_{\mathcal{R}}$	Width of resonance $\mathcal{R}$

$\Delta\eta$	Pseudorapidity difference
∂_μ	Four-vector derivative
ΔR	Angular separation
ϵ^{abc}	Totally antisymmetric tensor
ϵ_{xy}	Geometric transverse emittance
ζ	Phase of a gauge transformation
η	Pseudorapidity
θ	Polar angle
$\boldsymbol{\theta}$	Vector of nuisance parameters
λ	Higgs self-coupling parameter
κ	Track curvature
μ	Mass parameter of the Higgs potential
μ	Muon
μ_c	Combined signal strength
μ_{pu}	Pile-up mean value
$\langle\mu_{pu}\rangle$	Time-averaged pile-up mean value
ν_e	Electron neutrino
ν_μ	Muon neutrino
ν_τ	Tau neutrino
π	Archimede's constant
$\sigma_{1,2,3}$	Pauli matrices
σ_K	Cross section of generic process K
$\tilde{\sigma}_K$	Cross section of parton hard scattering process K
σ	Standard deviation
σ_H	Higgs production cross section
τ	Tau lepton
ϕ	Higgs field doublet
φ	Azimuthal angle
ϕ^*	Charge conjugate of the Higgs field
$\tilde{\phi}$	Antidoublet of the Higgs field
$\langle\phi\rangle$	Vacuum expectation value of the Higgs field
χ	Generic quantum field
ψ	Spinor field
$\bar{\psi}$	Dirac adjoint of a spinor field
$\psi^\dagger$	Hermitian adjoint of a spinor field
ψ_L	Left-handed spinor field
ψ_R	Right-handed spinor field

LIST OF ACRONYMS

ATLAS	A Toroidal LHC Apparatus, CERN experiment
BDT	Boosted decision trees
BR	Branching ratio of a decay
CERN	European Organization for Nuclear Research
CL	Confidence level
CMS	Compact Muon Solenoid, CERN experiment
CP	Combined charge conjugation and parity
CSC	Cathode strip chamber detector
Data/MC	Data-to-MC ratio
DY	Drell-Yan
EMCal	Electromagnetic calorimeter, ATLAS detector
EWSB	Electroweak symmetry breaking
FastSim	Fast-simulation
FCal	Forward calorimeter, ATLAS detector
FSR	Final-state radiation
FullSim	Full-simulation
ggF	Gluon fusion, Higgs production mode
GRL	GOODRUNLIST
HCal	Hadronic calorimeter, ATLAS detector
HEC	Liquid argon endcap calorimeter, ATLAS detector
HL-LHC	High-luminosity Large Hadron Collider program
HLT	High-level trigger, ATLAS detector
ID	Inner tracker, ATLAS detector
ISR	Initial-state radiation
JVT	Jet vertex tagger
L1	Level-1 trigger, ATLAS detector
LHC	Large Hadron Collider
LO	Leading-order approximation
MC	Monte Carlo, simulation
MDT	Monitored drift tube detector
ME	Matrix element

MLE	Maximum-likelihood estimator
MM	Resistive-strip micro-mesh gaseous chamber detector
MS	Muon spectrometer, ATLAS detector
MVA	Multivariate classification algorithm
NLL	Next-to-leading-logarithm approximation
NLO	Next-to-leading-order approximation
NNLO	Next-to-next-leading-order approximation
NP	Nuisance parameter
NSW	New small wheel, ATLAS detector
pdf	Probability density function
PDF	Parton distribution function
POI	Parameter of interest
PS	Parton showering
QCD	Quantum chromodynamics
RMS	Root-mean-square
SCT	Semiconductor tracker, ATLAS detector
SM	Standard Model
sTGC	Small-strip thin gap chamber detector
S/B	Signal-to-background ratio
TileCal	Tile hadronic calorimeter, ATLAS detector
TRT	Transition-radiation tracker, ATLAS detector
$t\bar{t}H$	Top fusion, Higgs production mode
UE	Underlying event
VBF	Vector boson fusion, Higgs production mode
VH	Higgs-strahlung, Higgs production mode
WP	Working point

BIBLIOGRAPHY

- [1] CMS COLLABORATION, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Physics Letters B, vol. 716, p. 30–61, 2012, [10.1016/j.physletb.2012.08.021], [eprint]
- [2] ATLAS COLLABORATION, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Physics Letters B, vol. 716, p. 1–29, 2012, [10.1016/j.physletb.2012.08.020], [eprint]
- [3] ATLAS COLLABORATION, *A search for the dimuon decay of the Standard Model Higgs boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, 2019, [eprint]
- [4] ATLAS COLLABORATION, *A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector*, Physics Letters B, vol. 812, p. 135980, 2021, [10.1016/j.physletb.2020.135980], [eprint]
- [5] M. E. PESKIN AND D. V. SCHROEDER, *An Introduction to quantum field theory*, Frontiers in Physics, Addison-Wesley, 1995
- [6] THE EUROPEAN MATHEMATICAL SOCIETY, *Encyclopedia of Mathematics: Einstein rule*, 2014, [eprint]
- [7] E. NOETHER, *Invariant variation problems*, Transport Theory and Statistical Physics, vol. 1, no. 3, pp. 186–207, 1971, [10.1080/00411457108231446], [eprint]
- [8] D. HESTENES, *Real Dirac Theory*, Advances in Applied Clifford Algebras, vol. 7, 1997, [eprint]
- [9] W. GREINER, S. SCHRAMM, AND E. STEIN, *Quantum chromodynamics; 3rd ed.*, Springer, 2007, [10.1007/978-3-540-48535-3], [eprint]
- [10] W. GREINER AND B. MÜLLER, *Gauge theory of weak interactions; 2nd ed.*, Springer, 1996, [10.1007/978-3-662-03323-4], [eprint]
- [11] W. PAULI, *On the Connection between Spin and Statistics*, Progress of Theoretical Physics, vol. 5, pp. 526–543, 1950, [10.1143/ptp/5.4.526], [eprint]
- [12] P. W. HIGGS, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett., vol. 13, pp. 508–509, 1964, [10.1103/PhysRevLett.13.508]
- [13] P. W. HIGGS, *Broken symmetries, massless particles and gauge fields*, Phys. Lett., vol. 12, pp. 132–133, 1964, [10.1016/0031-9163(64)91136-9], [eprint]

- [14] F. ENGLERT AND R. BROUT, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett., vol. 13, pp. 321–323, 1964, [[10.1103/PhysRevLett.13.321](#)], [eprint]
- [15] G. DEGRASSI, S. DI VITA, J. ELIAS-MIRÓ, J. R. ESPINOSA, G. F. GIUDICE, G. ISIDORI, AND A. STRUMIA, *Higgs mass and vacuum stability in the Standard Model at NNLO*, Journal of High Energy Physics, 2012, [[10.1007/jhep08\(2012\)098](#)], [eprint]
- [16] J. GOLDSTONE, A. SALAM, AND S. WEINBERG, *Broken Symmetries*, Phys. Rev., vol. 127, pp. 965–970, 1962, [[10.1103/PhysRev.127.965](#)]
- [17] PARTICLE DATA GROUP COLLABORATION, *Review of Particle Physics*, Progress of Theoretical and Experimental Physics, vol. 2020, 2020, [[10.1093/ptep/ptaa104](#)], [eprint]
- [18] MU-LAN COLLABORATION, *Improved Measurement of the Positive-Muon Lifetime and Determination of the Fermi Constant*, Phys. Rev. Lett., vol. 99, p. 032001, 2007, [[10.1103/PhysRevLett.99.032001](#)], [eprint]
- [19] J. ERLER AND M. SCHOTT, *Electroweak precision tests of the Standard Model after the discovery of the Higgs boson*, Progress in Particle and Nuclear Physics, vol. 106, pp. 68 – 119, 2019, [[10.1016/j.pnpnp.2019.02.007](#)]
- [20] V. BARGER, J. JIANG, P. LANGACKER, AND T. LI, *Gauge coupling unification in the Standard Model*, Physics Letters B, vol. 624, no. 3-4, pp. 233 – 238, 2005, [[10.1016/j.physletb.2005.08.019](#)], [eprint]
- [21] A. BISWAS, A. KUNDU, AND P. MONDAL, *Hierarchy problem and dimension-six effective operators*, Phys. Rev. D, vol. 102, p. 075022, 2020, [[10.1103/PhysRevD.102.075022](#)]
- [22] PLANCK COLLABORATION, *Planck 2018 results, VI, Cosmological parameters*, Astron. Astrophys., vol. 641, 2020, [[10.1051/0004-6361/201833910](#)], [eprint]
- [23] L. CANETTI, M. DREWES, AND M. SHAPOSHNIKOV, *Matter and antimatter in the universe*, New Journal of Physics, vol. 14, p. 095012, 2012, [[10.1088/1367-2630/14/9/095012](#)], [eprint]
- [24] P. HUET AND E. SATHER, *Electroweak baryogenesis and standard model CP violation*, Phys. Rev., vol. D51, pp. 379–394, 1995, [[10.1103/PhysRevD.51.379](#)], [eprint]
- [25] T. KAJITA, *Nobel Lecture: Discovery of atmospheric neutrino oscillations*, Rev. Mod. Phys., vol. 88, p. 030501, 2016, [[10.1103/RevModPhys.88.030501](#)], [eprint]
- [26] A. B. McDONALD, *Nobel Lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos*, Rev. Mod. Phys., vol. 88, p. 030502, 2016, [[10.1103/RevModPhys.88.030502](#)], [eprint]

- [27] P. F. DE SALAS, S. GARIAZZO, O. MENA, C. A. TERNES, AND M. TÓRTOLA, *Neutrino Mass Ordering from Oscillations and Beyond: 2018 Status and Future Prospects*, *Frontiers in Astronomy and Space Sciences*, vol. 5, 2018, [10.3389/fspas.2018.00036], [eprint]
- [28] K. BABU AND E. MA, *Radiative mechaniss for generating quark and lepton masses: some recent developments*, *Modern Physics Letters A*, vol. 04, no. 20, pp. 1975–1981, 1989, [10.1142/S0217732389002239], [eprint]
- [29] B. A. DOBRESCU AND P. J. FOX, *Quark and lepton masses from top loops*, *Journal of High Energy Physics*, vol. 2008, pp. 100–100, 2008, [10.1088/1126-6708/2008/08/100], [eprint]
- [30] S. WEINBERG, *Models of lepton and quark masses*, *Physical Review D*, vol. 101, 2020, [10.1103/physrevd.101.035020], [eprint]
- [31] B. S. BALAKRISHNA, *Fermion mass hierarchy from radiative corrections*, *Phys. Rev. Lett.*, vol. 60, pp. 1602–1605, 1988, [10.1103/PhysRevLett.60.1602]
- [32] S. P. MARTIN, *A supersymmetry primer*, *Advanced Series on Directions in High Energy Physics*, p. 1–98, 1998, [10.1142/9789812839657], [eprint]
- [33] B. BELLAZZINI, C. CSÁKI, AND J. SERRA, *Composite Higgses*, *The European Physical Journal C*, vol. 74, 2014, [10.1140/epjc/s10052-014-2766-x]
- [34] I. HINCHLIFFE AND A. MANOHAR, *The QCD Coupling Constant*, *Annual Review of Nuclear and Particle Science*, vol. 50, no. 1, pp. 643–678, 2000, [10.1146/annurev.nucl.50.1.643], [eprint]
- [35] D. F. GEESAMAN AND P. E. REIMER, *The sea of quarks and antiquarks in the nucleon*, *Reports on Progress in Physics*, vol. 82, p. 046301, 2019, [10.1088/1361-6633/ab05a7], [eprint]
- [36] T. R. S. A. OF SCIENCES, *Asymptotic freedom and quantum chromodynamics: the key to the understanding of the strong nuclear forces*, 2004, [eprint]
- [37] J. CARLSON, A. JAFFE, AND A. WILES, *The Millennium Prize Problems*, *Frontiers in Physics*, American Mathematical Society and Clay Mathematics Institute, 2006
- [38] LHC HIGGS CROSS SECTION WORKING GROUP [url]
- [39] LHC HIGGS CROSS SECTION WORKING GROUP, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, 2017, [eprint]
- [40] E. A. MOBS, *The CERN accelerator complex. Complexe des accélérateurs du CERN*, 2016, [eprint]
- [41] O. S. BRÜNING, P. COLLIER, P. LEBRUN, S. MYERS, R. OSTOJIC, J. POOLE, AND P. PROUDLOCK, *LHC Design Report*, CERN, 2004, [eprint]

- [42] D. BOUSSARD, E. CHIAVERI, E. HÄBEL, H. P. KINDERMANN, R. LOSITO, S. MARQUE, V. RÖDEL, AND M. STIRBET, *The LHC superconducting cavities*, p. 4 p, 1999, [eprint]
- [43] L. ROSSI, *Superconducting magnets for the LHC main lattice*, IEEE Trans. Appl. Supercond., vol. 14, pp. 153–158. 7 p, 2004, [10.1109/TASC.2004.829031], [eprint]
- [44] R. OSTOJIC, *The LHC Insertion Magnets*, IEEE Trans. Appl. Supercond., vol. 12, pp. 196–201. 7 p, 2002, [10.1109/TASC.2002.1018382], [eprint]
- [45] A. IJSPEERT, M. KARPPINEN, AND J. SALMINEN, *Design of corrector magnets for the LHC*, 1999, [10.5170/CERN-1999-001.137], [eprint]
- [46] CMS COLLABORATION, *CMS Physics: Technical Design Report Volume 1: Detector Performance and Software*, 2006, [eprint]
- [47] K. OYAMA, *ALICE detector status and upgrade plans*, EPJ Web Conf., vol. 49, p. 02002, 2013, [10.1051/epjconf/20134902002]
- [48] R. LEFÈVRE, *LHCb Status and Prospects*, pp. 87–100
- [49] FASER COLLABORATION, *FASER’s physics reach for long-lived particles*, Phys. Rev. D, vol. 99, p. 095011, 2019, [10.1103/PhysRevD.99.095011]
- [50] MoEDAL COLLABORATION, *Physics reach of MoEDAL at LHC: magnetic monopoles, supersymmetry and beyond*, 2016, [eprint]
- [51] TOTEM COLLABORATION, *The TOTEM Experiment at the LHC*, pp. 357–360, 2009, [eprint]
- [52] M. BONGI *et al.*, *LHCf Experiment: Physics Results*, Nucl. Part. Phys. Proc., vol. 279–281, pp. 125–129, 2016, [10.1016/j.nuclphysbps.2016.10.018]
- [53] I. BÉJAR ALONSO, O. BRÜNING, P. FESSIA, L. ROSSI, L. TAVIAN, AND M. ZERLAUTH, *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN Yellow Reports: Monographs, CERN, 2020, [10.23731/CYRM-2020-0010], [eprint]
- [54] W. HERR AND B. MURATORI, *Concept of luminosity*, 2006, [10.5170/CERN-2006-002.361]
- [55] ATLAS COLLABORATION, *Luminosity public results Run 2*, [url]
- [56] J. PEQUENAO, *Computer generated image of the whole ATLAS detector*, [url]
- [57] ATLAS COLLABORATION, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST, vol. 3, p. S08003, 2008, [10.1088/1748-0221/3/08/S08003]
- [58] ATLAS COLLABORATION, *ATLAS magnet system: Technical Design Report, 1*, 1997, [eprint]

- [59] J. PEQUENAO AND P. SCHAFFNER, *How ATLAS detects particles: diagram of particle paths in the detector*, [url]
- [60] ATLAS COLLABORATION, *ATLAS inner detector: Technical Design Report, 1*, Technical design report. ATLAS, CERN, 1997, [eprint]
- [61] K. POTAMIANOS, *The upgraded Pixel detector and the commissioning of the Inner Detector tracking of the ATLAS experiment for Run-2 at the Large Hadron Collider*, 2016, [eprint]
- [62] ATLAS COLLABORATION, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST, vol. 3, p. S08003. 437 p, 2008, [10.1088/1748-0221/3/08/S08003], [eprint]
- [63] ATLAS COLLABORATION, *ATLAS tile calorimeter: Technical Design Report*, Technical design report. ATLAS, CERN, 1996, [eprint]
- [64] ATLAS COLLABORATION, *ATLAS liquid-argon calorimeter: Technical Design Report*, Technical design report. ATLAS, CERN, 1996, [eprint]
- [65] ATLAS COLLABORATION, *ATLAS muon spectrometer: Technical Design Report*, Technical design report. ATLAS, CERN, 1997, [eprint]
- [66] ATLAS COLLABORATION, *Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s}=8$ TeV. Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s}=8$ TeV*, Eur. Phys. J. C, vol. C75, p. 120. 19 p, 2014, [10.1140/epjc/s10052-015-3325-9], [eprint]
- [67] ATLAS COLLABORATION, *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, 2011, [eprint]
- [68] ATLAS COLLABORATION, *Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*, Tech. Rep. CERN-LHCC-2012-022. LHCC-I-023, CERN, Geneva, 2012
- [69] ATLAS COLLABORATION, *Performance of the ATLAS muon triggers in Run 2*, Journal of Instrumentation, vol. 15, p. P09015–P09015, 2020, [10.1088/1748-0221/15/09/p09015], [eprint]
- [70] ATLAS COLLABORATION, *New Small Wheel Technical Design Report*, 2013, [eprint]
- [71] N. V. MAIRA, *Status and progress of the NSW*, ATLAS Upgrade Week, [url]
- [72] ATLAS COLLABORATION, *ATLAS level-1 trigger: Technical Design Report*, Technical design report. ATLAS, CERN, 1998, [eprint]
- [73] ATLAS COLLABORATION, *ATLAS high-level trigger, data-acquisition and controls: Technical Design Report*, Technical design report. ATLAS, CERN, 2003, [eprint]

- [74] ATLAS COLLABORATION, *ATLAS Forward Detectors for Measurement of Elastic Scattering and Luminosity*, Technical design report. ATLAS, CERN, 2008, [eprint]
- [75] B. ANDERSSON, G. GUSTAFSON, G. INGELMAN, AND T. SJÖSTRAND, *Parton fragmentation and string dynamics*, Physics Reports, vol. 97, pp. 31–145, 1983
- [76] T. D. GOTTSCHALK, *A Simple Phenomenological Model for Hadron Production From Low Mass Clusters*, Nucl. Phys. B, vol. 239, pp. 325–348, 1984, [10.1016/0550-3213(84)90252-9]
- [77] J. ALWALL, M. HERQUET, F. MALTONI, O. MATTELAER, AND T. STELZER, *Official documentation of the MADGRAPH generator*, [url]
- [78] S. FRIXIONE, P. NASON, AND C. OLEARI, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, Journal of High Energy Physics, vol. 2007, p. 070–070, 2007, [10.1088/1126-6708/2007/11/070], [eprint]
- [79] C. OLEARI, *The POWHEG BOX*, Nuclear Physics B - Proceedings Supplements, vol. 205–206, p. 36–41, 2010, [10.1016/j.nuclphysbps.2010.08.016], [eprint]
- [80] M. L. MANGANO, F. PICCININI, A. D. POLOSA, M. MORETTI, AND R. PITTAU, *Official documentation of the ALPGEN generator*, [url]
- [81] E. BOTHMANN, S. HOECHE, F. KRAUSS, M. SCHOENHERR, S. SCHUMANN, F. SIEGERT, AND K. ZAPP, *Official documentation of the SHERPA generator*, [url]
- [82] C. BIERLICH, N. DESAI, L. GELLERSEN, I. HELENIUS, L. LÖNNBLAD, S. MRENNNA, S. PRESTEL, C. PREUSS, T. SJÖSTRAND, P. SKANDS, M. UTHEIM, AND R. VERHEYEN, *Official documentation of the PYTHIA generator*, [url]
- [83] S. AGOSTINELLI, J. ALLISON, K. AMAKO, J. APOSTOLAKIS, H. ARAUJO, P. ARCE, M. ASAI, D. AXEN, AND S. BANERJEE, *Geant4—a simulation toolkit*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 506, no. 3, pp. 250–303, 2003, [10.1016/S0168-9002(03)01368-8]
- [84] ATLAS COLLABORATION, *Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2*, The European Physical Journal C, vol. 77, 2017, [10.1140/epjc/s10052-017-5225-7], [eprint]
- [85] W. LAMPL, S. LAPLACE, D. LELAS, P. LOCH, H. MA, S. MENKE, S. RAJAGOPALAN, D. ROUSSEAU, S. SNYDER, AND G. UNAL, *Calorimeter Clustering Algorithms: Description and Performance*, 2008, [eprint]
- [86] 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*, The European Physical Journal C, vol. 79, 2019, [10.1140/epjc/s10052-019-7140-6]

- [87] ATLAS COLLABORATION, *Electron and photon energy calibration with the ATLAS detector using 2015-2016 LHC proton-proton collision data*, Journal of Instrumentation, vol. 14, pp. P03017–P03017, 2019, [10.1088/1748-0221/14/03/p03017]
- [88] ATLAS COLLABORATION, *Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016*, The European Physical Journal C, vol. 79, 2019, [10.1140/epjc/s10052-019-6650-6], [eprint]
- [89] ATLAS COLLABORATION, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, The European Physical Journal C, vol. 77, 2017, [10.1140/epjc/s10052-017-5004-5], [eprint]
- [90] ATLAS COLLABORATION, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, The European Physical Journal C, vol. 77, 2017, [10.1140/epjc/s10052-017-5031-2], [eprint]
- [91] M. CACCIARI, G. P. SALAM, AND G. SOYEZ, *The anti-ktjet clustering algorithm*, Journal of High Energy Physics, vol. 2008, p. 063–063, 2008, [10.1088/1126-6708/2008/04/063], [eprint]
- [92] ATLAS COLLABORATION, *Jet energy scale and resolution measured in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, 2020, [eprint]
- [93] ATLAS COLLABORATION, *Tagging and suppression of pileup jets with the ATLAS detector*, 2014, [eprint]
- [94] ATLAS COLLABORATION, *Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV*, Journal of High Energy Physics, vol. 2018, 2018, [10.1007/jhep08(2018)089], [eprint]
- [95] ATLAS COLLABORATION, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 p – p collision data set at $\sqrt{s} = 13$ TeV*, arXiv preprint arXiv:2012.00578, 2020, [eprint]
- [96] ATLAS COLLABORATION, *Beam-induced and cosmic-ray backgrounds observed in the ATLAS detector during the LHC 2012 proton-proton running period*, Journal of Instrumentation, vol. 11, p. P05013–P05013, 2016, [10.1088/1748-0221/11/05/p05013], [eprint]
- [97] G. BARONE, W. A. LEIGHT, S. ROSATI, F. SFORZA, J. MEYER, R. DI NARDO, AND M. TROVATELLI, *Momentum resolution improvements with the inclusion of the Alignment Errors On Track*, 2018
- [98] LHC NSW WORKING GROUP [url]
- [99] A. SALZBURGER, S. TODOROVA, AND M. WOLTER, *The ATLAS Tracking Geometry Description*, tech. rep., CERN, Geneva, 2007

- [100] A. ABUSLEME, C. BÉLANGER-CHAMPAGNE, A. BELLERIVE, Y. BENHAMMOU, J. BOTTE, H. COHEN, M. DAVIES, Y. DU, T. KOFFAS, S. KULESHOV, B. LEFEBVRE, *et al.*, *Performance of a Full-Size Small-Strip Thin Gap Chamber Prototype for the ATLAS New Small Wheel Muon Upgrade*, Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment, vol. 817, 2015, [[10.1016/j.nima.2016.01.087](https://arxiv.org/abs/10.1016/j.nima.2016.01.087)]
- [101] Y. MINO, *ATLAS hardware-based Endcap Muon Trigger for future upgrades*, 2020, [eprint]
- [102] B. STELZER, *The New Small Wheel Upgrade Project of the ATLAS Experiment*, Nuclear and Particle Physics Proceedings, vol. 273-275, pp. 1160–1165, 2016, [[10.1016/j.nuclphysbps.2015.09.182](https://arxiv.org/abs/10.1016/j.nuclphysbps.2015.09.182)]
- [103] ATLAS COLLABORATION, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV*, The European Physical Journal C, vol. 78, 2018, [[10.1140/epjc/s10052-018-6288-9](https://arxiv.org/abs/10.1140/epjc/s10052-018-6288-9)], [eprint]
- [104] CMS COLLABORATION, *Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC*, Phys. Lett. B, vol. 744, p. 184. 24 p, 2014, [[10.1016/j.physletb.2015.03.048](https://arxiv.org/abs/10.1016/j.physletb.2015.03.048)], [eprint]
- [105] CMS COLLABORATION, *Search for the Higgs Boson Decaying to Two Muons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV*, Physical Review Letters, vol. 122, 2019, [[10.1103/physrevlett.122.021801](https://arxiv.org/abs/10.1103/physrevlett.122.021801)]
- [106] ATLAS COLLABORATION, *Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector*, Physics Letters B, vol. 738, pp. 68–86, 2014, [[10.1016/j.physletb.2014.09.008](https://arxiv.org/abs/10.1016/j.physletb.2014.09.008)]
- [107] ATLAS COLLABORATION, *Search for the Dimuon Decay of the Higgs Boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, Physical Review Letters, vol. 119, 2017, [[10.1103/physrevlett.119.051802](https://arxiv.org/abs/10.1103/physrevlett.119.051802)]
- [108] 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*, 2018, [eprint]
- [109] S. D. DRELL AND T.-M. YAN, *Massive Lepton-Pair Production in Hadron-Hadron Collisions at High Energies*, Phys. Rev. Lett., vol. 25, pp. 316–320, 1970, [[10.1103/PhysRevLett.25.316](https://arxiv.org/abs/10.1103/PhysRevLett.25.316)]
- [110] ATLAS COLLABORATION, *Measurement of the transverse momentum distribution of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C, vol. 80, p. 616. 28 p, 2019, [[10.1140/epjc/s10052-020-8001-z](https://arxiv.org/abs/10.1140/epjc/s10052-020-8001-z)], [eprint]

- [111] R. D. BALL, V. BERTONE, S. CARRAZZA, C. S. DEANS, L. DEL DEBBIO, S. FORTE, A. GUFFANTI, N. P. HARTLAND, J. I. LATORRE, J. ROJO, *et al.*, *Parton distributions with LHC data*, Nuclear Physics B, vol. 867, p. 244–289, 2013, [10.1016/j.nuclphysb.2012.10.003]
- [112] ATLAS COLLABORATION, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model*, 2016
- [113] T. SJÖSTRAND, S. ASK, J. R. CHRISTIANSEN, R. CORKE, N. DESAI, P. ILTEN, S. MRENNNA, S. PRESTEL, C. O. RASMUSSEN, AND P. Z. SKANDS, *An introduction to PYTHIA 8.2*, Computer Physics Communications, vol. 191, p. 159–177, 2015, [10.1016/j.cpc.2015.01.024], [eprint]
- [114] LHC HIGGS CROSS SECTION WORKING GROUP, *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, 2013, [eprint]
- [115] S. ALIOLI, P. NASON, C. OLEARI, AND E. RE, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP, vol. 06, p. 043, 2010, [10.1007/JHEP06(2010)043], [eprint]
- [116] K. HAMILTON, P. NASON, E. RE, AND G. ZANDERIGHI, *NNLOPS simulation of Higgs boson production*, Journal of High Energy Physics, vol. 2013, 2013, [10.1007/jhep10(2013)222], [eprint]
- [117] J. BUTTERWORTH, S. CARRAZZA, A. COOPER-SARKAR, A. D. ROECK, J. FELTESSE, S. FORTE, J. GAO, S. GLAZOV, J. HUSTON, Z. KASSABOV, *et al.*, *PDF4LHC recommendations for LHC Run II*, Journal of Physics G: Nuclear and Particle Physics, vol. 43, p. 023001, 2016, [10.1088/0954-3899/43/2/023001]
- [118] J. ALWALL, R. FREDERIX, S. FRIXIONE, V. HIRSCHI, F. MALTONI, O. MATTELAER, H.-S. SHAO, T. STELZER, P. TORRIELLI, AND M. ZARO, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, Journal of High Energy Physics, vol. 2014, 2014, [10.1007/jhep07(2014)079], [eprint]
- [119] R. D. BALL, V. BERTONE, S. CARRAZZA, C. S. DEANS, L. DEL DEBBIO, S. FORTE, A. GUFFANTI, N. P. HARTLAND, J. I. LATORRE, *et al.*, *Parton distributions for the LHC run II*, Journal of High Energy Physics, vol. 2015, 2015, [10.1007/jhep04(2015)040]
- [120] ATLAS COLLABORATION, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Journal of High Energy Physics, vol. 2014, 2014, [10.1007/jhep09(2014)145]
- [121] ATLAS COLLABORATION, *ATLAS Pythia 8 tunes to 7 TeV data*, 2014
- [122] C. ANASTASIOU, C. DUHR, F. DULAT, E. FURLAN, T. GEHRMANN, F. HERZOG, A. LAZOPOULOS, AND B. MISTLBERGER, *High precision determination of the gluon fusion Higgs boson cross-section at the LHC*, 2016, [eprint]

- [123] M. CICCOLINI, D. A., AND D. S., *Electroweak and QCD corrections to Higgs production via vector-boson fusion at the CERN LHC*, Physical Review D, vol. 77, 2008, [10.1103/physrevd.77.013002], [eprint]
- [124] O. BREIN, A. DJOUADI, AND R. HARLANDER, *NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders*, Physics Letters B, vol. 579, p. 149–156, 2004, [10.1016/j.physletb.2003.10.112], [eprint]
- [125] Y. ZHANG, W.-G. MA, R.-Y. ZHANG, C. CHEN, AND L. GUO, *QCD NLO and EW NLO corrections to $t\bar{t}H$ production with top quark decays at hadron collider*, Physics Letters B, vol. 738, p. 1–5, 2014, [10.1016/j.physletb.2014.09.022], [eprint]
- [126] E. BOTHMANN, G. SINGH CHAHAL, S. HÖCHE, J. KRAUSE, F. KRAUSS, S. KUTIMALAI, S. LIEBSCHNER, D. NAPOLETANO, M. SCHÖNHERR, H. SCHULZ, *et al.*, *Event generation with Sherpa 2.2*, SciPost Physics, vol. 7, 2019, [10.21468/sci-postphys.7.3.034], [eprint]
- [127] S. HÖCHE, F. KRAUSS, M. SCHÖNHERR, AND F. SIEGERT, *QCD matrix elements + parton showers. The NLO case*, Journal of High Energy Physics, vol. 2013, 2013, [10.1007/jhep04(2013)027]
- [128] S. FRIXIONE, E. LAENEN, P. MOTYLINSKI, C. WHITE, AND B. R. WEBBER, *Single-top hadroproduction in association with a W boson*, Journal of High Energy Physics, vol. 2008, p. 029–029, 2008, [10.1088/1126-6708/2008/07/029]
- [129] S. HÖCHE, S. PRESTEL, AND H. SCHULZ, *Simulation of vector boson plus many jet final states at the high luminosity LHC*, Physical Review D, vol. 100, 2019, [10.1103/physrevd.100.014024]
- [130] S. DULAT, T.-J. HOU, J. GAO, M. GUZZI, J. HUSTON, P. NADOLSKY, J. PUMPLIN, C. SCHMIDT, D. STUMP, AND C.-P. YUAN, *New parton distribution functions from a global analysis of quantum chromodynamics*, Physical Review D, vol. 93, 2016, [10.1103/physrevd.93.033006]
- [131] H.-L. LAI, M. GUZZI, J. HUSTON, Z. LI, P. M. NADOLSKY, J. PUMPLIN, AND C.-P. YUAN, *New parton distributions for collider physics*, Physical Review D, vol. 82, 2010, [10.1103/physrevd.82.074024]
- [132] M. L. MANGANO, F. PICCININI, A. D. POLOSA, M. MORETTI, AND R. PITTAU, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, Journal of High Energy Physics, vol. 2003, p. 001–001, 2003, [10.1088/1126-6708/2003/07/001], [eprint]
- [133] J. PUMPLIN, D. R. STUMP, J. HUSTON, H.-L. LAI, P. NADOLSKY, AND W.-K. TUNG, *New Generation of Parton Distributions with Uncertainties from Global QCD Analysis*, Journal of High Energy Physics, vol. 2002, p. 012–012, 2002, [10.1088/1126-6708/2002/07/012]

- [134] P. GOLONKA AND Z. WAS, *Next-to-leading logarithms and the PHOTOS Monte Carlo*, The European Physical Journal C, vol. 50, p. 53–62, 2007, [10.1140/epjc/s10052-006-0205-3]
- [135] ATLAS COLLABORATION, *Reconstruction of collinear final-state-radiation photons in Z decays to muons in $\sqrt{s}=7$ TeV proton-proton collisions.*, 2012, [eprint]
- [136] T. CHEN AND C. GUESTRIN, *XGBoost: A Scalable Tree Boosting System*, p. 785–794, 2016, [10.1145/2939672.2939785]
- [137] J. C. COLLINS AND D. E. SOPER, *Angular distribution of dileptons in high-energy hadron collisions*, Phys. Rev. D, vol. 16, pp. 2219–2225, 1977, [10.1103/PhysRevD.16.2219]
- [138] ATLAS COLLABORATION, *Muon reconstruction performance in early $\sqrt{s} = 13$ TeV data*, 2015
- [139] S. CHEONG, A. CUKIERMAN, B. NACHMAN, M. SAFDARI, AND A. SCHWARTZMAN, *Parametrizing the detector response with neural networks*, Journal of Instrumentation, vol. 15, p. P01030–P01030, 2020, [10.1088/1748-0221/15/01/p01030], [eprint]
- [140] M. OREGLIA, *A Study of the Reactions $\psi' \rightarrow \gamma\gamma\psi$* , 1980
- [141] J. PATEL AND C. READ, *Handbook of the Normal Distribution, Second Edition*, Statistics: A Series of Textbooks and Monographs, Taylor & Francis, 1996
- [142] ATLAS COLLABORATION, *Measurement of the Drell-Yan triple-differential cross section in pp collisions at $\sqrt{s} = 8$ TeV*, Journal of High Energy Physics, vol. 2017, 2017, [10.1007/jhep12(2017)059], [eprint]
- [143] V. BERTONE, S. CARRAZZA, AND J. ROJO, *APFEL: A PDF evolution library with QED corrections*, Computer Physics Communications, vol. 185, p. 1647–1668, 2014, [10.1016/j.cpc.2014.03.007], [eprint]
- [144] A. BUCKLEY, J. FERRANDO, S. LLOYD, K. NORDSTRÖM, B. PAGE, M. RÜFENACHT, M. SCHÖNHERR, AND G. WATT, *LHAPDF6: parton density access in the LHC precision era*, The European Physical Journal C, vol. 75, 2015, [10.1140/epjc/s10052-015-3318-8]
- [145] S. L. ADLER, *Theories of the Fine Structure Constant α* , pp. 73–84, 1973
- [146] PARTICLE DATA GROUP COLLABORATION, *Review of Particle Physics*, Phys. Rev. D, vol. 98, p. 030001, 2018, [10.1103/PhysRevD.98.030001]
- [147] F. JAMES AND M. ROOS, *Minuit: A System for Function Minimization and Analysis of the Parameter Errors and Correlations*, Comput. Phys. Commun., vol. 10, pp. 343–367, 1975, [10.1016/0010-4655(75)90039-9]

- [148] R. BRUN AND F. RADEMAKERS, *ROOT - An Object Oriented Data Analysis Framework*, Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86, [10.5281/zenodo.848818]
- [149] W. VERKERKE AND D. KIRKBY, *The RooFit toolkit for data modeling*, 2003, [eprint]
- [150] F. HAIGHT AND O. R. S. OF AMERICA, *Handbook of the Poisson Distribution*, Operations Research Society of America. Publications in operations research, Wiley, 1967
- [151] J. ALDRICH, *R.A. Fisher and the making of maximum likelihood 1912-1922*, Statistical Science, vol. 12, no. 3, pp. 162 – 176, 1997, [10.1214/ss/1030037906]
- [152] G. COWAN, K. CRANMER, E. GROSS, AND O. VITELLS, *Asymptotic formulae for likelihood-based tests of new physics*, The European Physical Journal C, vol. 71, 2011, [10.1140/epjc/s10052-011-1554-0], [eprint]
- [153] A. READ, *Presentation of search results: theCLstechnique*, Journal of Physics G: Nuclear and Particle Physics, vol. 28, pp. 2693–2704, 2002, [10.1088/0954-3899/28/10/313]
- [154] LHC HIGGS CROSS SECTION WORKING GROUP, A. DAVID, A. DENNER, M. DUEHRSEN, M. GRAZZINI, C. GROJEAN, G. PASSARINO, M. SCHUMACHER, M. SPIRA, G. WEIGLEIN, AND M. ZANETTI, *LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle*, 2012, [eprint]
- [155] ATLAS AND CMS COLLABORATION, *Review of Particle Physics*, JHEP, vol. 08, p. 045. 70 p, 2016, [10.1007/JHEP08(2016)045], [eprint]
- [156] ATLAS COLLABORATION, *Measurements of the Higgs boson production and decay rates and coupling strengths using p – p collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment*, Eur. Phys. J. C, vol. 76, no. 1, p. 6, 2016, [10.1140/epjc/s10052-015-3769-y], [eprint]
- [157] ATLAS COLLABORATION, *Projections for measurements of Higgs boson cross sections, branching ratios, coupling parameters and mass with the ATLAS detector at the HL-LHC*, 2018, [eprint]
- [158] ATLAS COLLABORATION, *Prospects for the measurement of the rare Higgs boson decay $H \rightarrow \mu\mu$ with 3000 fb^{-1} of pp collisions collected at $\sqrt{s} = 14 \text{ TeV}$ by the ATLAS experiment*, tech. rep., CERN, Geneva, 2018
- [159] CMS COLLABORATION, *Evidence for Higgs boson decay to a pair of muons*, Journal of High Energy Physics, vol. 2021, 2021, [10.1007/jhep01(2021)148], [eprint]

ACKNOWLEDGEMENTS

Evening rain comes down gently here in Amsterdam, and the sudden ringing of the *Science Park* gate reminds me that it's time to head off. Before locking my office door one last time, I take a look at the empty grey desk in the corner, where nothing of mine lays around anymore. So, this is it.

While going down the very same stairs I took all these years, I realise how much of a home Nikhef always felt to me: a safe space where I could grow into the person I am. Unsurprisingly, leaving is hard. But I carry a bright luggage full of awesome memories, and I feel extremely rich. And more than the science, the music and the cities, it is the people I met along the way who made it all worth it: those who supported me, helped me and guided me; those who understood me or made me understand; those who stood by my side when things were hard; and those who joined me in crazy or more ordinary adventures. If you're reading these pages, you're probably one of them.

First of all, I would like to express my heartfelt gratitude to my promoter and co-promoter, Wouter Verkerke and Lydia Brenner. Thank you for believing in me from the very first day, and for even succeeding in the exhausting task of convincing me to do the same. Wouter, you'll always be a true inspiration for me, not only for your enlightening expertise, but also for your ability to sit down with anyone, even a first-year student like I was, and really listen to what they have to say. Thank you for always making the time to patiently explain some more statistics to me. Lydia, I truly admire your determination and dedication, and your talent in describing complex things in an accessible way. You've always been my main supporter, and during these long four years you've become so much more than just a supervisor and a colleague: a friend.

I would also like to thank my doctorate committee, for taking the time to read my thesis and provide valuable feedback: Wim Beenakker, Stan Bentvelsen, Fabio Cerutti, Auke-Pieter Colijn, Tristan Du Pree, Elisabetta Pallante and Tina Pollmann. Auke-Pieter, thank you for also being a caring C3 member, assisting me throughout the entire scope of my PhD career. Tristan, thanks for showing me around on my very first day at Nikhef, for laughing at my dumb meeting jokes (*Alice-not-the-experiment*) and for your strong interest towards *Higgs* $\mu\mu$.

This PhD really taught me a lot. Especially, that the path towards big achievements is not a lonely journey. The results presented in this thesis, in fact, were only possible thanks to the rich collaboration of too many brilliant minds, who constantly guided me with enthusiasm and confidence.

I owe a lot to the members of the NSW and $H \rightarrow \mu^+ \mu^-$ ATLAS research groups. In particular I would like to thank Hongtao Yang, Fabio Cerutti, Miha Muškinja

and Xiangyang Ju: you showed me how great it is to work in an enthusiastic, supportive team, and I will always remember our discussions about fit ranges and spurious signals with a proud and grateful smile on my face. Fabio, I am sincerely honoured I could meet you, and even more that you accepted to be a member of my committee. Hongtao, I would have been lost without your kindness, and your unfailing passion and knowledge. I hope our paths will cross again (although possibly not under *unblinding* circumstances!).

At Nikhef, I was part of the great "extended" ATLAS group. I wish to thank all the staff members, postdocs and students that populated our corridor, not only for the many fruitful meetings, but also for the coffee breaks, the lunches, the Friday *borrels*, the outings canoeing and biking and the crazy Veldhoven nights, and for generally making my PhD the most fun adventure I could imagine. Marcel, thank you for welcoming me to the ITk team and even trusting me with picking expensive sensors to buy. Peter, thanks for always being happy to share your vast knowledge not only about the muon system, but also about philosophy and art. Alessio, Anamika, Andrea, Andrea Vis, Ann-Kathrin, Ash, Birgit, Bob, Brian, Broos, Bryan, Carlo, Carlo, Carsten, Daniil, Dylan, Edwin, Emma, Evelin, Federica, Flavia, Florian, Geoffrey, Hannah, Ivan, JJ, Jordy, Kees, Luca, Lucia, Lucrezia, Marc, Marion, Marko, Marten, Matous, Matteo, Michiel, Milo, Osama, Pepijn, Polina, Rahul, Stefano, Terry, Tim, Veronica, Zef, Zhuoran... you are so many, I really hope I'm not forgetting anyone! It's been a pleasure to meet you all.

Kees and Brian, I really enjoyed being TA with you two, discussing pointers and even finding compiler bugs together! And Brian, also thanks for the help with thesis printing! Rahul, thank you for the sporty events in Geneva and for the house and job hunting tips. Ann-Kathrin, thank you for "supervising" me during our nights out in Geneva, it was absolutely needed. Birgit, I enjoyed our *Sinterklaas* parties, our summer swims in Amsterdam and our many online chats about just anything. Terry, thanks for the job search suggestions and for sending me your thesis via mail, it was a very nice gift! Marten, my Dutch summary would not be here without you! *Dankje* for being my translator on such short notice, I wish you all the best for your PhD. Edwin, I've never met anyone who dislikes sunlight as much as I do. Thank you for patiently tolerating my crazy housing situation, even when I was not-so-secretly storing washing machines in our office.

Federica, I am happy we got to share most of our PhD years, part of them as officemates even! Thank you for the advice, for our nice lunches/dinners, and for always finding the time to meet me whenever you passed by Amsterdam. Ivan, my dear friend, ex-colleague and housemate, thank you for always making me feel at home, I am so glad I met you. Michhhhiel, *you cat-like Dutchie*, thank you for getting all my silly jokes, for the fries, burgers and beers at CERN, for jumping in German rivers with me, and for just always being there for me whenever I needed a friend. Anamika, we went through so many adventures together! I still remember the day we met at the *BND*. Who would have thought that, after randomly sharing a room in Callantsoog, you would become part of my family? There's always a place for you where I am.

There are also many other wonderful people I met at Nikhef, CERN, in Amsterdam, Geneva and around the world which I absolutely want to mention. Eleftheria, I'm grateful for our nice chats, coffee walks and pink and blue cocktails (hopefully many more to come!), and for you being so patient with me during my thesis and job hunting phase. And grazie to the Italian *Sotto al sole* Nikhef team: Michele, Fabrizia and Veronica. You were among the first people I met in The Netherlands and you really helped me taking my first steps here. I would also like to thank my PhD Council colleagues: Zhanna, Marc, Brian, Igor, Lennart, Erik, Ruben, Maria, Avnish, Bouke, Alessio, Anamika, Serena and Alexandra. We did good things together (Brian: *all these things that we've done!* ♪). And thanks to Oğul and Yvonne for our long online and offline chats, to Diogo for the risky skating nights in Geneva, to Hanna for the tea breaks in building 42, to Gianmarco and Gianluca for the Veldhoven fun and banking help, and to Corrado for planning many NL Italian dinners.

I was even lucky enough to be adopted by the *cool kids* of LHCb. Thank you for inviting me to your parties, *Secret Santas*, deathly table football matches and Friday night dinners. In particular thanks to Cristina (I know you were waiting for this line!) for a memorable *Divali* French dinner, for the cocktails and for the lockdown video calls, to Maurício for being a valuable member of the *It's my birthday adventures* crew, to Aleksandra for the nice hiking trips, to Miriam for the walks in Vondelpark and, of course, to Jordy, for being my *paranymph*, for taking care of my plants whenever I'm gone and for being my sweet and caring Dutch brother, *Eeeek*, *Egggg!*

Not less important, my gratitude goes to Joan, Ed, Pieter and Nancy for helping me dealing with the Dutch and Swiss formalities. In no way I could have succeeded without your help. And finally, I would like to thank my two amazing singing teachers: Claudia e Beth. You welcomed me in a world full of sound and joy, and I feel blessed for being part of such a nice music community. Looking forward to the day we can perform publicly again!

My first day at Nikhef really seems like yesterday and, at the same time, like a long life ago. But I would probably not have started this journey in the first place without the support of the many extraordinary people that I already had in my life.

A big thanks goes to the CMS LNF-INFN team (Luigi, Davide, Giovanna, Luciano), who encouraged me to submit my PhD application even if it meant that I would change group and country, and in particular to Stefano Bianco, whom I always remember with gratitude and affection. *Avanti tutta!*

I also cannot forget my beautiful Roman friends: those I met in high-school, who are still happy to see me whenever I come back, and those from my university days: Elisa, Giovanni, Clara, Beatrice, Alessandro Rocchi, Alessandro (Di Marco) Aquilani, Deborah and Daniele *electronut*. Daniele, I am honoured to be your friend and even if we don't meet often, it always feels like no time has passed. Elisa, thanks for always lending me a hand and for lovingly supporting me during my weakest time, patiently trying to convince me that I deserved so much better (p.s.: you were right!). Debbie, you're Roman in your heart! I hope we can meet soon

in Bonn, Amsterdam or Rome again! Clara and *Beatricia*, I love all our memories together, you will always be my two favourite *GirlsOfScience*! And Clara, thanks for teaching me how to *mettere i paletti*, for being a great listener and for always, always sticking with me through the good and bad times. Giovanni, I cannot imagine my life without you in it, and I tell myself that I can't be that bad of a person if you decided to be my friend.

Finally, thanks to my family. *Nonneta*, non mi hai mai fatto mancare il tuo amore sotto forma di gnocchi, fettuccine, *pizza al gusto tutto* e ciambelloni. E grazie ai nonni Emanuele, Ugo e Bravetta che sono sempre nel mio cuore. E a zia Alda, agli zii Piero ed Elena, Maurizio e Maria Teresa, Sergio e Stefania, Ivanoe e Nancy, Melita e tutti i *Sammarchetti*, e ai miei cugini grandi e piccini. In particolare grazie a Simone, *sei mejo te*. Yet another special thanks goes to my life companions: Moncicci, Cicero and Morgana, who silently sat next to me through most of my life changes, and would probably deserve a PhD of their own. You saved me more than I could ever have saved you.

There's then an entire group of people I met through my father over the years. They stayed after his departure, effectively becoming part of my family: Susanna (o Annasusa!), Giancarlo lo zio veterinario, Paola Zibba, Achille, Luigi, Cinzia e Umberto, Annamaria la Carletti e Raul... sono una persona fortunata ad avervi incontrati. E Giorgia, porta avanti la staffetta! E ancora, Maurizio Picchio e Silvanicchia, Brunella, Daniele, Davide con la sua presenza sensibile e Paola Giorgi, che non dimentica neanche un 16 del mese. Last but not least, Adrian, it was a great honour to meet you and I will always be one of your biggest fans. You can do anything you set your mind to. And if you don't, *te meno*.

Most importantly, grazie alla mia mamma e al mio papà. I will never cease to be amazed at how lucky I am to have had outstanding parents like you two, and how often I managed to take that for granted. Mamma, *Ho mamma cara!* Non è stato facile, ma sono una donna onesta, giusta e fiera grazie a te. Ti voglio tantissimo bene, *mille*. Papà, volevi tanto vedere questa tesi finita. In quell'aula sarai seduto in prima fila, orgoglioso e attento. Sempre paziente accanto a me, mentre salgo tutte le scale del mondo. *Grazie*.

SUMMARY

The history of knowledge is the history of humankind.

Around the world, library shelves are stacked with the tales of centuries, collecting everything that was ever thought, observed, invented and perfected since the beginning of civilisation. Today we live by incredible scientific discoveries, supported with elegant theories and monumental experiments. And yet an even wider, unfamiliar territory echoes on the edge of our achievements. Questions that we could not have contemplated before gain dimension and texture as we lunge deeper into what is still unknown, led by the torchlight of what we have learned so far. *What are we made of? How did the universe begin, and will it end?* Particle physics strives to explore many of the possible answers, with the ultimate goal of painting a complete and consistent picture of nature.

One of its biggest achievements is the so-called *Standard Model*, a theoretical framework that describes the physical world in terms of a set of symmetries and basic building blocks. It postulates that visible matter is mostly made up of elementary particles called fermions, and that the interactions that manifest in nature are

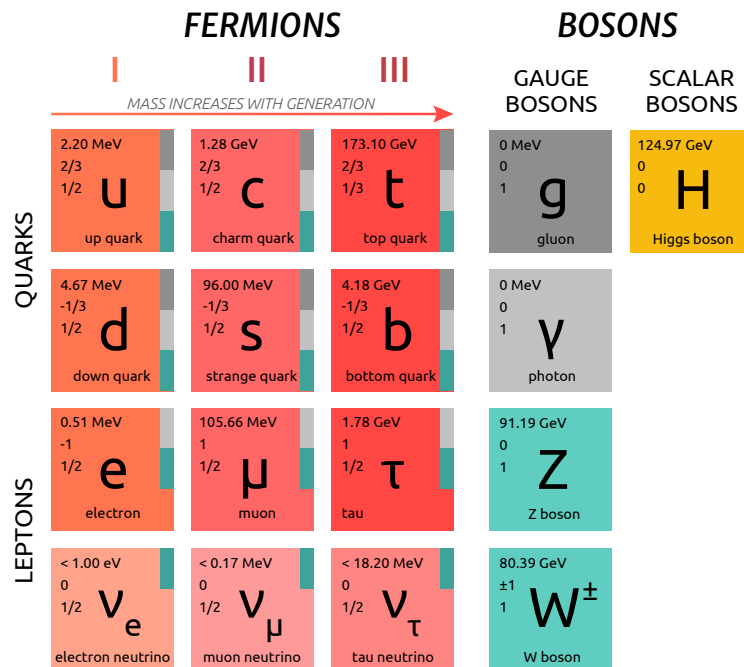


Figure 1: Particle content of the Standard Model of particle physics, consisting of three generations of fermions that make up matter, of gauge bosons that mediate the interactions, and of a scalar Higgs boson that is connected to the mass generation mechanism. From top to bottom, the quantities on the left side of the squares indicate the mass, the electric charge and the spin of each particle.

exchanges of force carriers called gauge bosons [figure 1]. Additionally a complex scalar field ϕ , called the *Higgs field*, is supposed to permeate the universe, and to give mass to the other particles via the so-called *Brout-Englert-Higgs mechanism* [figure 2]. Its potential $V(\phi)$ exhibits a set of degenerate, physically equivalent minima. In the early stages of the universe, a particular minimum from this set was selected, introducing a preferred direction in the ϕ -space and breaking the so-called *electroweak symmetry*. This symmetry breaking produced the electromagnetic and weak forces observed in nature with their respective boson carriers, $W^\pm$ and Z , and a massive *Higgs boson*, which is the physical particle associated to the Higgs field. By interacting with the Higgs field, the $W^\pm$ and Z gauge bosons and most of the known fermions acquire a mass, whose value depends on the strength of their interactions or, in jargon, couplings, with the Higgs field itself. Gauge boson masses appear as a direct consequence of symmetry breaking, deriving naturally from the equations that govern the Higgs kinematics. Fermions, on the other hand, require the addition of dedicated mass-generating components, which define specific Higgs interactions called *Yukawa interactions*. The mathematical form of each mass term is completely fixed by the model, but the mass values and the coupling strengths are both incorporated as free parameters in the formalism, and must be extrapolated experimentally.

The Standard Model's predictions have been extensively validated by a large number of experiments, proving its effectiveness in describing physics phenomena with great accuracy and within a wide energy range. However, its equations are far from providing a complete understanding of nature. Some theoretical shortcomings and experimental measurements cannot be explained within its current framework, suggesting that it is not a conclusive model of fundamental physics, but only the effective representation of a much larger theory.

For example, the very Brout-Englert-Higgs mechanism is still insufficient to properly explain the measured fermion masses. According to the observations, charged fermions can be grouped into three generations: each one is an exact copy of the others, with the only difference residing in the masses of the particles in it. Their values increase significantly across generations, spanning from the few MeV of the first to the hundreds of MeV of the third. This peculiar hierarchy seems to follow some natural rule that the theory, treating masses as free parameters, is not able to justify. It is not known why each fermion has a given mass, why fermions cluster into generations spaced in mass and why the top quark, the heaviest particle, has a mass approximately equal to the vacuum expectation value of the Higgs field. It is thus reasonable to wonder if the postulated Yukawa interactions are correct, and if they are part of a more complex scheme.

During the last decades, various attempts were made at building models that can address the issue in an exhaustive way, mostly resorting to possible extensions of the Standard Model. The topic gained renewed interest in the past year, as a result of the growing experimental possibilities that allow to explore the fermion sector at increasing levels of detail. Nevertheless, all hypotheses remain only speculative

so far, and the need for experimental input is critical.

The European organisation for nuclear research, or *CERN*, operates the largest particle physics facility in the world, and provides the necessary experimental tools to test the Standard Model. It hosts an accelerator complex located underground beneath the Swiss-French border, in which two counter-rotating proton beams are produced, accelerated and then brought to meet head-on along the ring of the *Large Hadron Collider*, the highest-energy collider in the world. Such powerful collisions are able to break protons into their internal constituents, which can then interact and recombine into other particles, such as the Higgs boson, that could not be produced otherwise.

Various experiments collect and analyse the resulting data. Among them is the general-purpose ATLAS detector, which is designed to investigate a wide range of phenomena, from Higgs physics to searches for new exotic particles. Together with the CMS experiment, in the summer of 2012 the ATLAS Collaboration announced the discovery of a particle compatible with the predicted Higgs boson, marking a historic scientific milestone and filling in the last missing piece of the Standard Model. That day, the long quest that aims at a complete comprehension of Higgs physics and of the origin of mass began.

All the studies conducted throughout the following years probed many characteristics of the Higgs boson, and found no deviations from the predictions of the Standard Model. Its spin and parity, as well as its interactions with gauge bosons and fermions of the third generation, have all been measured and shown to be

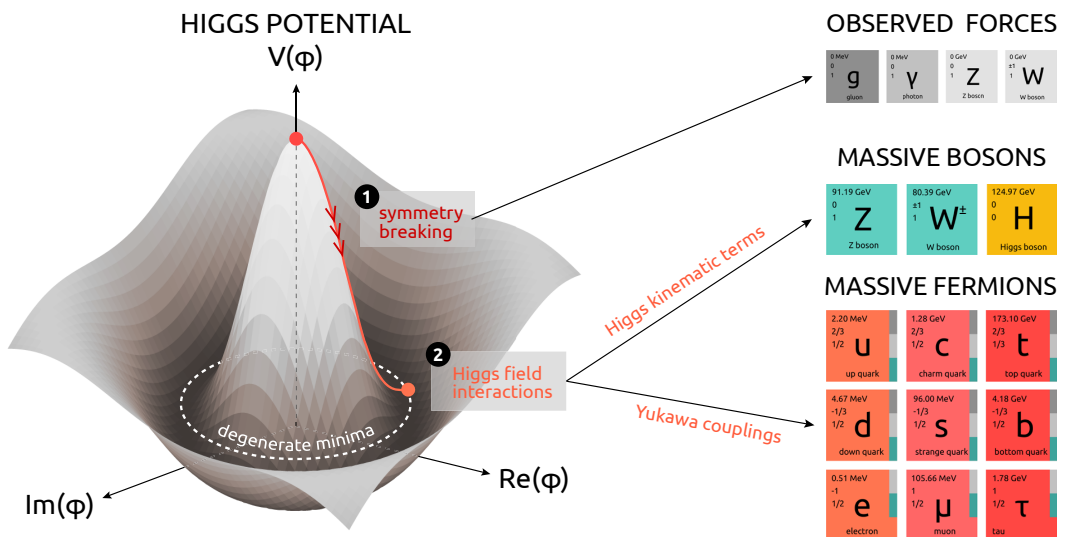


Figure 2: Pictorial visualisation of the Brout-Englert-Higgs mechanism: the Higgs potential with its degenerate set of minima (white circumference) leads to electroweak symmetry breaking when tending towards a status of least energy (orange curve). As a result, the electromagnetic and weak forces, their respective gauge bosons and the Higgs boson arise. The obtained non-zero vacuum expectation value defines the interactions of the Higgs fields with gauge bosons and fermions, which acquire mass in the process.

consistent with the theoretical expectations. However, interactions with lighter fermions have still not been observed, as the lower masses involved lead to rarer physics phenomena that require much more data than what was available until now.

Second generation fermions have intermediate mass values, and thus intermediate assumed Yukawa couplings. Therefore they can be explored today, thanks to the large number of collision events recorded during Run 2 of the Large Hadron Collider. The easiest way to directly probe their interactions is by measuring the decay rates of the Higgs boson into fermion-antifermion pairs. In this context, the $H \rightarrow \mu^+ \mu^-$ channel constitutes the best candidate. Despite its tiny branching ratio (only $\sim 0.02\%$ of all Higgs decays result in a muon pair), it offers a very clean final state that consists of two isolated muons with opposite charge, which are easily detectable and identifiable. Therefore, it gives the opportunity to investigate an interaction of the Higgs boson that has never been studied before, and could pave the way to completely different physics scenarios.

Large Hadron Collider events have already been scrutinised for the presence of a $H \rightarrow \mu^+ \mu^-$ signal, using the full Run 1 data collected at centre-of-mass energies of 7 and 8 TeV, and studying the first 79.8 fb^{-1} of Run 2 collisions at 13 TeV. The available statistics was not sufficient to claim an observation, and upper limits on the $H \rightarrow \mu^+ \mu^-$ decay rate have been provided. They state that, if it exists, the sought signal must be less than a given value, which was set to 2.9 times the Standard Model's expectation by CMS [104, 105] and to 2.1 times the Standard Model's expectation by ATLAS [106–108]. Today, a more precise search for this channel can be performed, profiting from the 139 fb^{-1} dataset collected by the end of Run 2, which almost doubles the one of the previous analyses. This is the study presented in this thesis.

THE SEARCH FOR $H \rightarrow \mu^+ \mu^-$ DECAYS WITH THE ATLAS DETECTOR

The topology of a Standard Model $H \rightarrow \mu^+ \mu^-$ decay consists of a muon and an antimuon. Therefore, the signal is expected to appear as a resonance peak in the dimuon invariant mass spectrum, sitting over a smoothly falling background made of all the unrelated processes that lead to muon pairs in the final state. This translates into a rather simple data analysis strategy, in which collision events containing at least two muons of opposite charge are selected and scrutinised for the presence of an excess traceable to the decay of Higgs bosons.

However, the extremely high expected number of background events, as opposed to the tiny $H \rightarrow \mu^+ \mu^-$ branching ratio, transforms a generally straightforward study into a very challenging one. The signal-to-background ratio is in fact at the per-mille level, and requires each step of the analysis to be performed very carefully, focusing on maximising the signal. The background, dominated by Drell-Yan events in which a neutral gauge boson decays into a muon pair, must instead be suppressed, and its remainder must be accurately modelled.

The selected events are classified into twenty distinct categories, on the basis of the multiplicity and kinematic properties of the objects they contain [figure 3].

Rectangular cuts on physical quantities such as jets, missing transverse momentum, photons and electrons are first used to target the four main production modes of the Higgs boson: gluon fusion (ggF), vector boson fusion (VBF), Higgs-strahlung (VH) and top fusion ($t\bar{t}H$). Then, multivariate algorithms are applied to the resulting data subsets, combining the information of multiple discriminating variables such as the particle momenta and pseudorapidities to further separate the signal from the background. Each resulting category is optimised separately, to exploit the common characteristics of the events it contains maximising the sensitivity of the search.

A critical stage of the analysis involves the construction of statistical models that describe the signal and background distributions. In particular, given the

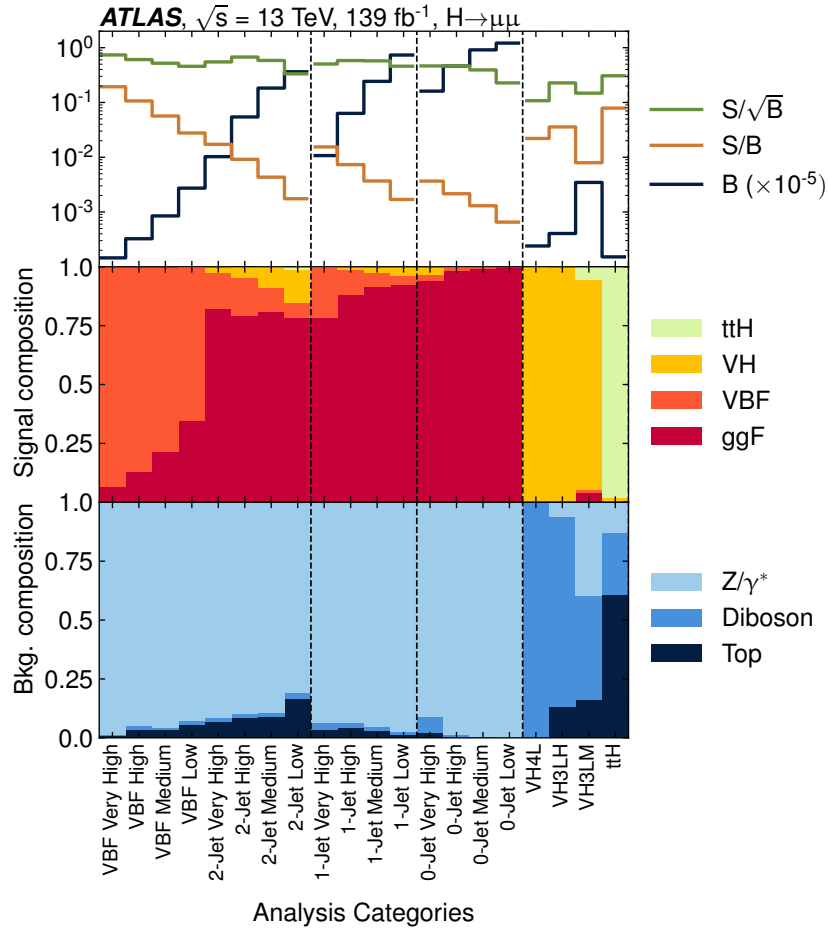


Figure 3: Overview of the categories defined in the $H \rightarrow \mu^+\mu^-$ analysis. The top panel shows the counting significance, expressed as the ratio $S/\sqrt{B}$ between the expected Standard Model signal and the square-root of the background, the signal-to-background ratio S/B and the number of background events B in the signal region. The middle panel shows the expected contributions of the different production modes to the signal, and the bottom panel shows the background composition.

low signal-to-background ratio, the slightest inaccuracy in the description of the background can significantly affect the detection of the searched decay. The signal is modelled using a parametric Crystal Ball function, which combines a central Gaussian component with two power-law tails, and is able to describe not only the Higgs resonance, but also features such as the experimental detector response that affect lower or higher mass regions.

The background model is built by multiplying a rigid core component, which addresses the main Drell-Yan trend, with an empirical function specific to each category. The core is a physics-inspired analytical function that combines theoretical calculations of the leading-order Drell-Yan cross section and experimental resolution effects. The empirical component is chosen among power-law functions and exponentials of polynomials with a variable number of floating parameters, using a set of strict criteria based on fits to the data sidebands and to multiple high-statistics Monte Carlo simulations. The obtained background description is then thoroughly validated on dedicated simulation samples, to estimate and minimise the potential mismodelling and its associated systematic uncertainty.

Using the selected models, a combined maximum-likelihood fit to the observed data is finally performed, treating all categories simultaneously. This allows to extract the $H \rightarrow \mu^+ \mu^-$ signal strength μ_c , defined as the ratio of the observed signal over its Standard Model expectation. Additionally, the associated statistical significance of the search is estimated.

RESULTS

The full Run 2 dataset proved to be still insufficient to claim a direct observation of the $H \rightarrow \mu^+ \mu^-$ decay. After performing the signal-plus-background fits [figure 4, left], in fact, the measured value of the signal strength is $\mu_c = 1.2 \pm 0.6$, which does not allow to draw definitive conclusions about the presence of the searched signal. However, an upper limit on the $H \rightarrow \mu^+ \mu^-$ branching ratio can be estimated, assuming the Standard Model Higgs production cross section. This is found to be $\text{BR}(H \rightarrow \mu^+ \mu^-) < 4.7 \times 10^{-4}$ at 95% confidence level, and is reported in the most recent ATLAS publication on the topic [4]. The corresponding observed significance is 2.0 standard deviations with respect to the hypothesis of no signal, while the expected significance is 1.7 standard deviations. This is already close to the 3 standard deviations threshold, which is considered to mark the first evidence for a given particle physics phenomenon.

When compared to the previous $H \rightarrow \mu^+ \mu^-$ search published by ATLAS in Run 1 [107], these results represent a 250% improvement: three quarters of this improvement depend on the reduced statistical uncertainty brought by the larger analysed dataset, and one quarter can be attributed to the more advanced analysis techniques, in particular the multivariate classification and the precise background modelling detailed in the present thesis.

The obtained measurements contribute significantly to the current, most advanced knowledge about the Higgs boson's interactions with fermions. Despite not leading to an observation of this decay yet, they can still be interpreted in terms

of a Higgs coupling strength to muons. Together with the analysis published by CMS on the same dataset [159], they provide the most precise measurement to date of such coupling. Its value seems to strongly hint towards the existence of an interaction between muons and the Higgs boson compatible with the Standard Model predictions, although still limited by large statistic uncertainties [figure 4, right].

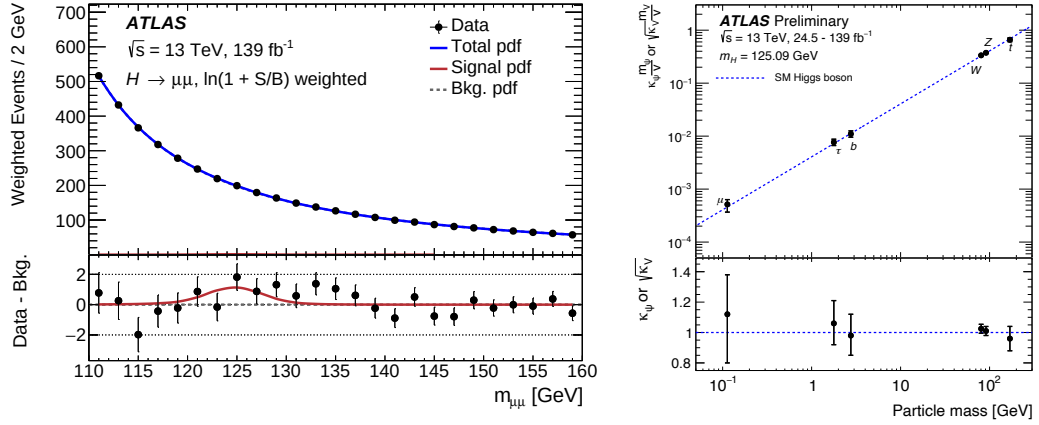


Figure 4: Left: observed dimuon invariant mass spectrum in all the $H \rightarrow \mu^+\mu^-$ analysis categories combined. The data points are shown in black with their statistic uncertainties, and the blue line is the fitted signal-plus-background model. The bottom panel compares the signal model, normalised to its best-fit value, to the difference between the data and the background model. The events are weighted by $\ln(1 + S/B)$, where S and B are the observed signal and background yields respectively. Right: coupling strengths of the Standard Model Higgs boson as a function of the mass of the particles with which it interacts, calculated using the full Run 2 data. The blue dashed line shows the Standard Model's expectations, and the bottom pad reports the values normalised to such expectations [156].

OUTLOOK

The sensitivity to the $H \rightarrow \mu^+\mu^-$ channel, with its small number of expected signal events and relatively clean final state, depends greatly on the amount of available collisions. In this respect, the future of this search is bright, as consistently larger datasets will characterise the future programme of the Large Hadron Collider. With the additional data expected at the end of Run 3, the combined ATLAS and CMS $H \rightarrow \mu^+\mu^-$ results might already reach 5 standard deviations in the next few years, meeting the official observation threshold. Further future studies, aided by the unprecedented amounts of data expected in the final, high-luminosity phase of the Large Hadron Collider, will then provide precision measurements of the $H \rightarrow \mu^+\mu^-$ interaction, probing closely the mass generation mechanism. The scientific community is possibly still decades away from attaining a definitive understanding of the rules of nature, but great discoveries are certainly, and excitingly ahead.

SAMENVATTING

De geschiedenis van kennis is de geschiedenis van de mensheid.

Overall ter wereld staan bibliotheken vol met de verhalen van door de eeuwen, met daarin alles verzameld wat ooit is gedacht, waargenomen, uitgevonden en geperfectioneerd sinds het begin van de beschaving. Vandaag leven we door middel van ongelooflijke wetenschappelijke ontdekkingen, ondersteund door elegante theorieën en monumentale experimenten. En toch weerklinkt aan de rand van onze prestaties een nog groter, onbekend terrein. Vragen die we eerder niet hadden kunnen overwegen, krijgen meer diepgang en textuur naarmate we verder reiken in wat nog onbekend is, geleid door het fakkellicht van wat we tot nu toe hebben geleerd. *Waar zijn we van gemaakt? Hoe is het universum begonnen, en zal het eindigen?* De deeltjesfysica streeft ernaar veel van de mogelijke antwoorden te onderzoeken, met het ultieme doel een volledig en consistent beeld van de natuur te schetsen.

Een van zijn grootste successen is het zogenaamde *Standaardmodel*, een theoretisch kader dat de fysieke wereld beschrijft in termen van een reeks symmetrieën en fundamentele bouwstenen. Het stelt dat zichtbare materie voornamelijk bestaat

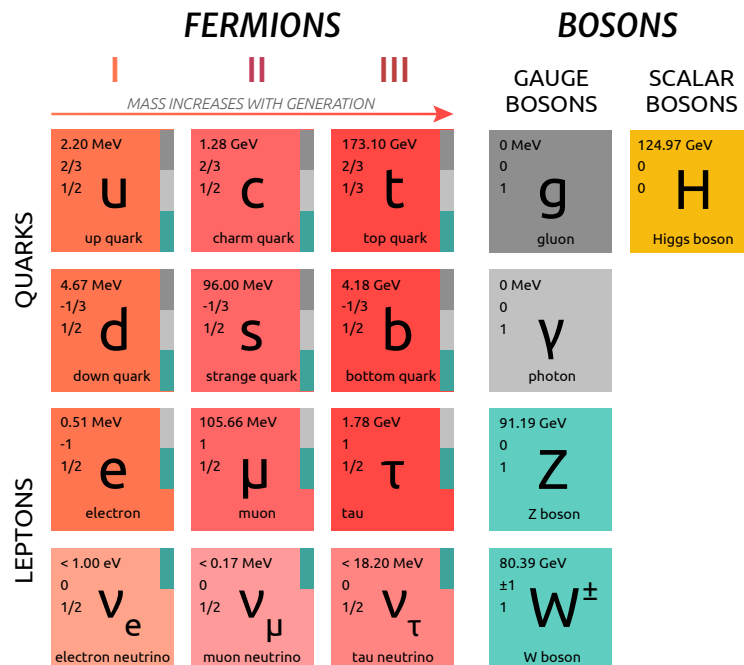


Figure 1: Deeltjesinhoud van het Standaard Model van de deeltjesfysica, bestaande uit drie generaties fermionen die materie vormen, ijkbosonen die de interacties bemiddelen, en één scalair Higgsboson dat verbonden is met het mechanisme van massageneratie. Van boven naar beneden geven de grootheden aan de linkerkant van de vierkantjes de massa, de elektrische lading en de spin van elk deeltje aan.

uit elementaire deeltjes die fermionen worden genoemd, en dat de interacties die in de natuur tot uiting komen uitwisselingen zijn van krachtdragende deeltjes die ijkbosonen worden genoemd [figuur 1]. Bovendien wordt verondersteld dat een complexwaardig scalair veld, het Higgsveld genaamd, het heelal doordringt en massa geeft aan de andere deeltjes via het zogenaamde *Brout-Englert-Higgs-mechanisme* [figuur 2]. De potentiaal van dit veld, $V(\phi)$, vertoont een reeks ontaarde, fysisch equivalente minima.

In de vroege stadia van het heelal werd een bepaald minimum uit deze reeks gekozen, waardoor er een voorkeursrichting in de ϕ -ruimte werd geïntroduceerd en de zogenaamde *elektrozwakke symmetrie* werd gebroken. Het breken van de symmetrie leidde tot de in de natuur waargenomen elektromagnetische en zwakke wisselwerkingen met hun bijbehorende ijkbosonen, $W^\pm$ en Z , en een massief *Higgsboson*, dat het fysische deeltje is dat geassocieerd wordt met het Higgsveld. Door wisselwerking met het Higgsveld krijgen de $W^\pm$ en Z ijkbosonen en de meeste bekende fermionen een massa, waarvan de waarde afhangt van de sterkte van hun wisselwerkingen of, in jargon, koppelingen, met het Higgsveld zelf. De massa's van de ijkbosonen zijn een rechtstreeks gevolg van de symmetriebreking en vloeien op natuurlijke wijze voort uit de vergelijkingen die de kinematica van de Higgs beschrijven. Fermionen, daarentegen, vereisen de toevoeging van specifieke massa genererende componenten, die specifieke Higgs interacties definiëren, de zogenaamde *Yukawa interacties*. De wiskundige vorm van elke massaterm ligt volledig vast in het model, maar de waardes van de massa's en de koppelingen zijn beide als vrije parameters in het formalisme opgenomen, en moeten experimenteel worden geëxtrapoleerd.

De voorspellingen van het Standaardmodel zijn uitvoerig gevalideerd door een groot aantal experimenten, waarmee de effectiviteit van het model voor het beschrijven van natuurkundige verschijnselen met grote nauwkeurigheid en binnen een breed energiebereik wordt bewezen. De vergelijkingen van het Standaardmodel bieden echter bij lange na geen volledig begrip van de natuur. Sommige theoretische tekortkomingen en experimentele metingen kunnen niet binnen het huidige raamwerk worden verklaard, wat suggereert dat het geen sluitend model van de fundamentele natuurkunde is, maar slechts de effectieve weergave van een veel grotere theorie.

Zo is het Brout-Englert-Higgs mechanisme bijvoorbeeld nog steeds onvoldoende om de gemeten massa's van de fermionen goed te verklaren. Volgens de waarnemingen kunnen de geladen fermionen in drie generaties worden ingedeeld: elke generatie is een exacte kopie van de andere, met als enig verschil de massa's van de deeltjes die er deel van uitmaken. De waarden van de massa's nemen aanzienlijk toe tussen de generaties, lopend van enkele MeV van de eerste tot honderden MeV van de derde. Deze eigenaardige hiërarchie lijkt een natuurlijke regel te volgen die de theorie, die de massa's als vrije parameters ziet, niet kan rechtvaardigen. Het is niet bekend waarom elk fermion een gegeven massa heeft, waarom fermionen clusteren in generaties gescheiden door massa en waarom de topquark, het zwaarste deeltje, een massa heeft die ongeveer gelijk is aan de vacuümverwachtingswaarde

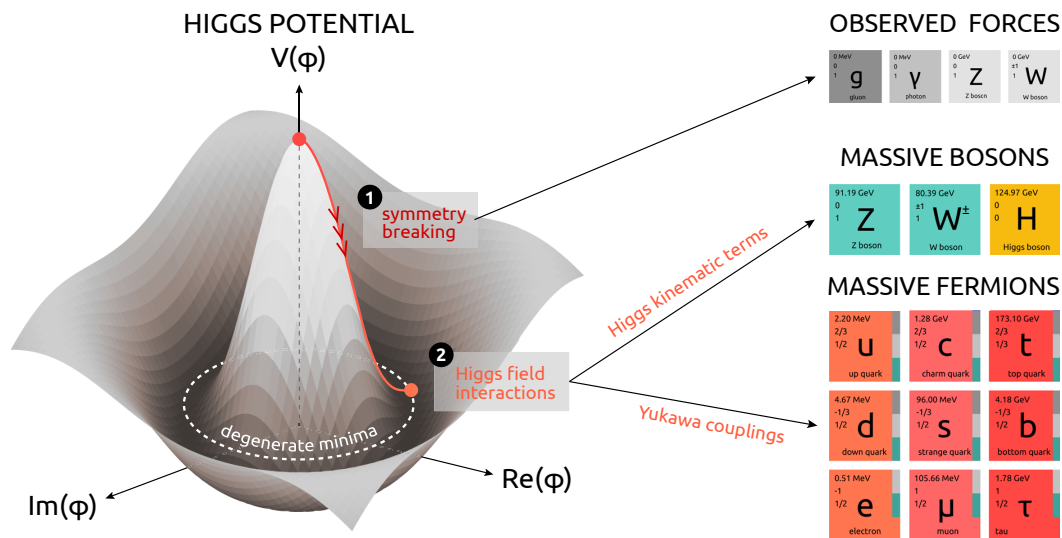


Figure 2: Visualisatie van het Brout-Englert-Higgs mechanisme: aan de linkerkzijde leidt de Higgs potentiaal met zijn ontaarde reeks minima (witte cirkel) tot elektrozwakke symmetriebreking bij het vervallen naar een toestand van de minste energie (oranje curve). Als gevolg hiervan ontstaan de elektromagnetische en zwakke krachten en hun respectievelijke ijkbosonen. De verkregen niet-nul vacuümverwachtingswaarde bepaalt de interacties van de Higgsvelden met ijkbosonen en fermionen, die in het proces massa verwerven.

van het Higgsveld. Het is dus redelijk om af te vragen of de veronderstelde Yukawa interacties juist zijn, en of ze deel uitmaken van een complexer schema.

In de afgelopen decennia zijn verschillende pogingen gedaan om modellen te bouwen die het probleem uitvoerig kunnen aanpakken, waarbij meestal een beroep werd gedaan op mogelijke uitbreidingen van het Standaardmodel. Het onderwerp is het afgelopen jaar opnieuw in de belangstelling gekomen als gevolg van de groeiende experimentele mogelijkheden die het mogelijk maken de fermionsector met steeds meer detail te onderzoeken. Desalniettemin blijven alle hypothesen tot dusver slechts speculatief en is de behoefte aan experimentele input van cruciaal belang.

De Europese organisatie voor kernonderzoek, *CERN*, opereert de grootste deeltjesfysica-installatie ter wereld en levert de nodige experimentele instrumenten om het Standaardmodel te testen. Het herbergt een ondergronds complex van deeltjesversnellers onder de Zwitsers-Franse grens, waar twee tegengesteld draaiende protonenbundels worden geproduceerd, versneld en vervolgens frontaal tegen elkaar gebracht langs de ring van de *Large Hadron Collider*, de deeltjesversneller met de hoogste energie ter wereld. Dergelijke krachtige botsingen zijn in staat protonen op te breken tot hun interne bestanddelen, die dan kunnen wisselwerken en hercombineren tot andere deeltjes, zoals het Higgsboson, die anders niet zouden kunnen worden geproduceerd.

Diverse experimenten verzamelen en analyseren de resulterende data. Een van hen is de algemene detector *ATLAS*, die is ontworpen om een breed scala van

verschijnselen te onderzoeken, van Higgsfysica tot het zoeken naar nieuwe exotische deeltjes. Samen met het CMS experiment heeft het ATLAS samenwerkingsverband in de zomer van 2012 de ontdekking bekendgemaakt van een deeltje dat compatibel is met het voorspelde Higgsboson, waarmee een historische wetenschappelijke mijlpaal werd gehaald en het laatste ontbrekende stukje van het Standaardmodel werd opgevuld. Die dag begon de lange zoektocht naar een volledig begrip van het Higgsfysica en van de oorsprong van massa.

Alle onderzoeken die in de jaren daarop werden verricht, onderzochten vele kenmerken van het Higgsboson, en vonden geen afwijkingen met de voorspellingen van het Standaardmodel. De spin en pariteit ervan, alsmede de interacties met bosonen en fermionen van de derde generatie, zijn allemaal gemeten en in overeenstemming met de theoretische verwachtingen. Wisselwerkingen met lichtere fermionen zijn echter nog steeds niet waargenomen, omdat de bijbehorende lagere massa's tot zeldzamere fysische verschijnselen leiden waarvoor veel meer gegevens nodig zijn dan wat tot nu toe beschikbaar was.

Fermionen van de tweede generatie hebben middelhoge massa's, en dus middelhoge veronderstelde Yukawa koppelingen. Daarom kunnen zij vandaag de dag worden onderzocht, dankzij het grote aantal botsingen dat tijdens Run 2 van de Large Hadron Collider is opgeslagen. De makkelijkste manier om hun wisselwerkingen rechtstreeks te peilen is door het meten van de vervalsnelheden van het Higgsboson in fermion-antifermion paren. In deze context is het $H \rightarrow \mu^+ \mu^-$ kanaal de beste kandidaat. Ondanks de kleine vertakkingsratio (slechts $\sim 0.02\%$ van alle vervallen van het Higgs boson resulteert in een muonen-paar), biedt het een zeer schone eindtoestand die bestaat uit twee geïsoleerde muonen met tegengestelde lading, die gemakkelijk te detecteren en te identificeren zijn. Daarom biedt het de mogelijkheid om een wisselwerking van het Higgsboson te onderzoeken die nog nooit eerder is bestudeerd, en zou het de weg kunnen banen naar totaal verschillende fysische scenario's.

De botsingen gezien in de Large Hadron Collider zijn inmiddels al onderzocht voor een $H \rightarrow \mu^+ \mu^-$ signaal, gebruik makend van de volledige Run 1 dataset met massamiddelpuntsenergieën van 7 en 8 TeV, en van de eerste 79.8 fb^{-1} aan data van Run 2 met botsingen met een massamiddelpuntsenergie van 13 TeV. De beschikbare hoeveelheid data was niet toereikend om een waarneming te claimen, en er zijn bovengrenzen voor de vervalskans van $H \rightarrow \mu^+ \mu^-$ vastgesteld. De resultaten stellen dat, als het verval bestaat, het gezochte signaal kleiner moet zijn dan een bepaalde waarde, die door CMS op 2.9 maal de verwachte waarde van het Standaard Model werd gesteld [104, 105] en door ATLAS op 2.1 maal de verwachte waarde van het Standaard Model [106–108]. Tegenwoordig kan er nauwkeuriger naar dit kanaal worden gezocht met behulp van de dataset van 139 fb^{-1} die aan het eind van Run 2 is verzameld, wat bijna het dubbele is van die van de vorige analyses. Dat is het onderzoek dat in dit proefschrift wordt gepresenteerd.

HET ZOEKEN NAAR $H \rightarrow \mu^+ \mu^-$ VERVAL MET DE ATLAS DETECTOR

De topologie van een $H \rightarrow \mu^+ \mu^-$ verval volgens het Standaard Model bestaat uit een muon en een antimuon. Het kan daarom verwacht worden dat het signaal zal verschijnen als een resonantiepiek in het dimuon invariante massaspectrum, over een gelijkmatig dalende achtergrond die bestaat uit alle ongerelateerde processen die leiden tot muonenparen in de eindtoestand. Dit vertaalt zich in een vrij eenvoudige strategie voor gegevensanalyse, waarbij de botsingen die ten minste twee muonen van tegengestelde lading produceerden, worden geselecteerd en onderzocht op de aanwezigheid van een overmaat die kan worden herleid tot het verval van Higgsbosonen.

Het extreem hoge verwachte aantal achtergrondgebeurtenissen, in tegenstelling tot de piepkleine $H \rightarrow \mu^+ \mu^-$ vertakkingsratio, maakt van een over het algemeen eenvoudig onderzoek echter een zeer uitdagend onderzoek. De signaal/achtergrondverhouding ligt in feite op het promille niveau, en vereist dat elke stap van de analyse zeer zorgvuldig wordt uitgevoerd, met de nadruk op de maximalisatie van het signaal. De achtergrond, die wordt gedomineerd door het Drell-Yan proces waarin een neutraal ijkboson in een muonenpaar vervalst, moet daarentegen worden onderdrukt, en het restant moet nauwkeurig worden gemodelleerd.

De geselecteerde data is ingedeeld in twintig afzonderlijke categorieën, op basis van de meervoudigheid en de kinematische eigenschappen van de objecten die het bevat [figuur 3]. Rechthoekige sneden op fysische grootheden zoals jets, ontbrekend transversaal momentum, fotonen en elektronen worden eerst gebruikt om de vier voornaamste productieprocessen van het Higgsboson aan te pakken: gluon-gluonfusie (ggF), vector boson fusie (VBF), Higgs-strahlung (VH) en top fusie (ttH). Vervolgens worden multivariate algoritmes toegepast op de resulterende categorieën, waarbij de informatie van meerdere discriminerende variabelen, zoals de impuls en pseudorapiditeit van de deeltjes, wordt gecombineerd om het signaal verder te scheiden van de achtergrond. Elk van de resulterende categorieën worden afzonderlijk geoptimaliseerd, om gebruik te maken van de gemeenschappelijke kenmerken van de gebeurtenissen die ze bevatten, zodat de signaalgevoeligheid zo hoog mogelijk wordt.

Een kritieke fase van de analyse is het opstellen van statistische modellen die de signaal- en achtergrondverdelingen beschrijven. In het bijzonder, gegeven het lage verhouding van signaal tot achtergrond, kan de kleinste onnauwkeurigheid in de beschrijving van de achtergrond significant veel invloed uitoefenen op de waarneming van het gezochte verval. Het signaal wordt gemodelleerd met behulp van een parametrische Crystal Ball functie, die een centrale Gaussische component combineert met twee door machtsfuncties beschreven staarten, en in staat is niet alleen de resonantiepiek van de Higgs te beschrijven, maar ook kenmerken zoals de experimentele detectorrespons die van invloed zijn op lagere of hogere massa's.

Het achtergrondmodel wordt opgebouwd door vermenigvuldiging van een vaste kerncomponent, die de voornaamste Drell-Yan trend beschrijft, met een empirische functie die specifiek is voor elke categorie. De kerncomponent is een op de fysica geïnspireerde analytische functie die theoretische berekeningen van de laagste-

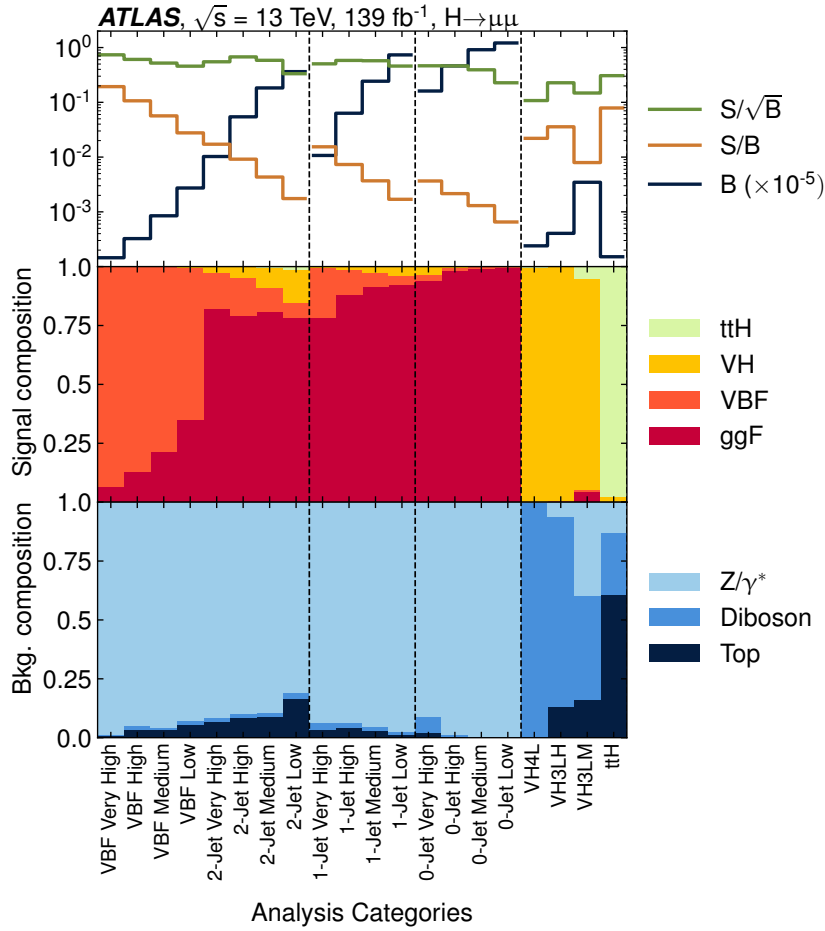


Figure 3: Overzicht van de categorieën gedefinieerd in de $H \rightarrow \mu^+ \mu^-$ analyse. Het bovenste paneel toont de significantie voor een telexperiment, uitgedrukt als de verhouding $S/\sqrt{B}$ tussen het verwachte Standaardmodel-sigitaal en de wortel van de achtergrond, de signaal-achtergrondverhouding S/B en het aantal achtergrondgebeurtenissen B in het signaalgebied. Het middelste paneel toont de verwachte bijdragen van de verschillende productiemodi aan het signaal, en het onderste paneel toont de achtergrondsamenstelling.

orde werkzame Drell-Yan doorsnede combineert met resolutie-effecten van het experiment. De empirische component wordt gekozen uit machtsfuncties en exponentiële functies van polynomen met een variabel aantal vrije parameters, aan de hand van een reeks strikte criteria op basis van fits op zijbanden van de data en op meerdere Monte Carlo simulaties met hoge statistiek. Het verkregen achtergrondmodel wordt vervolgens uitvoerig gevalideerd aan de hand van specifieke simulatiesteekproeven om de potentiële verkeerde modellering en de daarmee samenhangende systematische onzekerheid in te schatten en tot een minimum te beperken.

Met behulp van de geselecteerde modellen wordt ten slotte een gecombineerde maximum likelihood fit met de waargenomen data uitgevoerd, waarbij alle cate-

gorieën tegelijk worden behandeld. Dit maakt het mogelijk om de signaalsterkte μ_c van het $H \rightarrow \mu^+ \mu^-$ proces, gedefinieerd als de verhouding van het waargenomen signaal tot de verwachting van het Standaardmodel, te berekenen. Bovendien wordt de statistische significantie van het signaal geschat.

RESULTATEN

De volledige reeks data van Run 2 bleek nog steeds onvoldoende om een directe waarneming van het verval van $H \rightarrow \mu^+ \mu^-$ te kunnen claimen. Na het uitvoeren van de signaal-plus-achtergrond fits [figuur 4, links], is de gemeten waarde van de signaalsterkte $\mu_c = 1.2 \pm 0.6$, waaruit geen definitieve conclusies getrokken kunnen worden over de aanwezigheid van het gezochte signaal. Er kan echter wel een bovengrens worden geschat voor de vertakkingsratio van $H \rightarrow \mu^+ \mu^-$, uitgaande van de werkzame doorsnede van het Standaard Model Higgsbosonproductie. Deze bovengrens is vastgesteld op $\text{BR}(H \rightarrow \mu^+ \mu^-) < 4.7 \times 10^{-4}$ met een betrouwbaarheidsniveau van 95%, en is vermeld in de meest recente publicatie van ATLAS over dit onderwerp [4]. De bijbehorende waargenomen significantie bedraagt 2.0 standaardafwijkingen ten opzichte van de hypothese van geen signaal, terwijl de verwachte significantie 1.7 standaardafwijkingen bedraagt. Dit ligt al dicht bij de drempel van 3 standaardafwijkingen, wat wordt beschouwd als het eerste bewijs voor een bepaald verschijnsel in de deeltjesfysica.

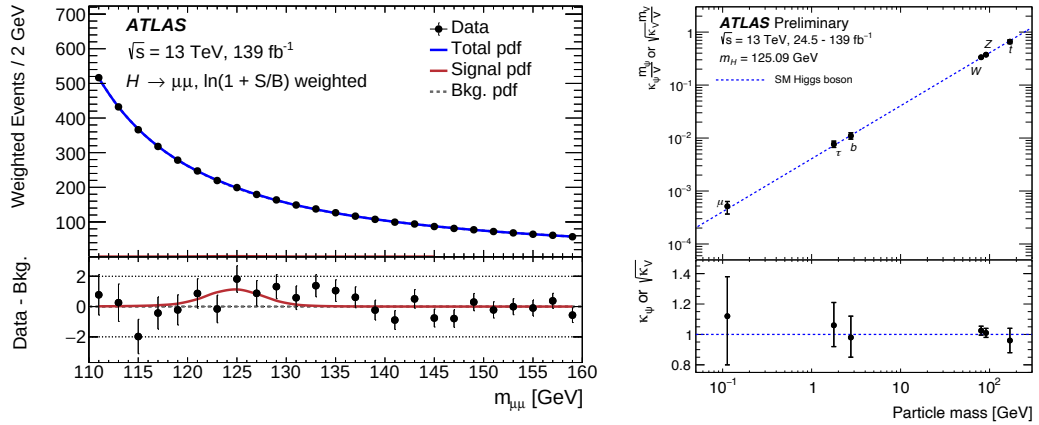


Figure 4: Links: waargenomen dimuon invariant massaspectrum in alle $H \rightarrow \mu^+ \mu^-$ analysecategorieën gecombineerd. De datapunten zijn in zwart weergegeven met hun statistische onzekerheden, en de blauwe lijn is het passende signaal-plus-achtergrondmodel. Het onderste paneel vergelijkt het signaalmodel, genormaliseerd naar zijn best passende waarde, met het verschil tussen de gegevens en het achtergrondmodel. De gebeurtenissen worden gewogen met $\ln(1 + S/B)$, waarbij S en B respectievelijk de waargenomen signaal- en achtergrondopbrengsten zijn. Rechts: koppelingssterkten van het Standaard Model Higgs boson als functie van de massa van de deeltjes waarmee het een interactie heeft, berekend met de volledige Run 2 gegevens. De blauwe stippellijn toont de verwachtingen van het Standaardmodel, en het onderste blokje geeft de waarden genormaliseerd naar deze verwachtingen [156].

In vergelijking met de vorige zoektocht naar $H \rightarrow \mu^+\mu^-$ die door ATLAS in Run 1 werd gepubliceerd [107], vormen deze resultaten een verbetering van 250%: driekwart van deze verbetering is toe te schrijven aan de verminderde statistische onzekerheid als gevolg van de grotere geanalyseerde dataset, en een kwart aan de meer geavanceerde analysetechnieken, in het bijzonder de multivariate classificatie en de nauwkeurige modellering van de achtergrond die in dit proefschrift worden beschreven.

De verkregen metingen dragen aanzienlijk bij tot de huidige, meest geavanceerde kennis over de wisselwerkingen van het Higgsboson met fermionen. Hoewel ze nog niet geleid hebben tot een waarneming van dit verval, kunnen ze toch geïnterpreteerd worden in termen van de sterkte van de koppeling van het Higgsboson aan de muonen. Samen met de door CMS gepubliceerde analyse van dezelfde dataset [159], leveren ze de meest precieze meting van een dergelijke koppeling tot op heden. De waarde lijkt sterk te wijzen op het bestaan van een wisselwerking tussen muonen en het Higgsboson die verenigbaar is met de voorspellingen van het Standaard Model, hoewel het nog steeds beperkt wordt door grote statistische onzekerheden [figuur 4, rechts].

VOORUITZICHTEN

De gevoeligheid voor het $H \rightarrow \mu^+\mu^-$ kanaal, met zijn kleine aantal verwachte signaalgebeurtenissen en relatief schone eindtoestand, hangt sterk af van het aantal beschikbare botsingen. In dit opzicht is de toekomst van dit onderzoek rooskleurig, aangezien steeds grotere datasets karakteriserend zullen zijn voor het toekomstige programma van de Large Hadron Collider. Met de extra data die aan het einde van Run 3 verwacht wordt, zouden de gecombineerde ATLAS en CMS $H \rightarrow \mu^+\mu^-$ resultaten de 5 standaardafwijkingen al in de komende jaren kunnen bereiken, waarmee de officiële waarnemingsdrempel wordt behaald.

Verder toekomstig onderzoek, geholpen door de ongekende hoeveelheden gegevens die worden verwacht in de laatste fase met hoge luminositeit van de Large Hadron Collider, zullen dan precisie metingen van de $H \rightarrow \mu^+\mu^-$ wisselwerking opleveren, waarbij het mechanisme van massageneratie nauwkeurig zal worden onderzocht. De wetenschappelijke gemeenschap is wellicht nog tientallen jaren verwijderd van een definitief begrip van de regels van de natuur, maar grote ontdekkingen liggen zeker, en opwindend, in het verschiet.