



Thesis

Thesis to opt for the degree of Master
of science, Physical Mention

25th May 2023



Initial approach to the physics of Higgs bosons decaying to tau leptons and b-quarks with the ATLAS experiment.

Sergio Fernández

The ATLAS Experiment is preparing for data taking during the LHC Run3, with a corresponding increase in instantaneous luminosity (pile-up) and beam energy, and consequently a large event rate and size. This scenario takes into account multiple improvements and updates based on the increase in stored data. This document put the focus of the software improvements, as the Trigger Monitoring Code, Data-Quality Trigger and some experimental studies of the Higgs particles in later specific framework used in ATLAS. Part of the beginning of the data collection is the Trigger Code and in order to cope with the more stringent data-taking condition, the ATLAS software underwent an upgrade to a multi-threading architecture that implied a major rewriting of the ATLAS software framework (Athena). Specifically, the Tau Offline Monitoring Code was completely modified for Run 3 which is part of the main stage of the experiment process to postulate Tau candidates as well as exotic searches. Also, for the same Monitoring Code was performed a Data-Quality study related to the search of a better and upgrade reference suitable for the current monitoring status.

Finally, in some later stage when the Higgs studies are performed, a work about the standard calibrated dataset format (CxAOD) collected in background samples with a new version Monte Carlo generator Sherpa 2.2.11 is done, due to analysis of the Higgs boson pair production (HH) in the $b\bar{b}\tau\tau$ channel decay.

Contents

1	Introduction	4
1.1	The Standard Model	5
1.2	The Standard Model and the Higgs Boson	6
1.3	The Standard Model gauge theory	7
1.4	The Higgs boson and Higgs pair production	16
1.5	Beyond The Standard Model	20
2	ATLAS detector	22
2.1	The Large Hadron Collider	22
2.2	Proton-proton collisions and simulation of physics processes	25
2.3	The ATLAS detector	30
3	Trigger system	37
3.1	Trigger menu design	38
3.2	Athena Multi-Threading architecture	40
4	Legacy implementation & analysis	40
4.1	Results	42
5	Truth quantities in Trigger Tau monitoring	42
5.1	Results	44
6	Di-tau systems in trigger tau monitoring.	46
7	χ^2 test between different reprocessing	49
7.1	χ^2 - test for comparison of unweighted histograms	49
8	Samples improvement for non-resonant $b\bar{b}\tau_{lep}\tau_{had}$ channel	55
8.1	Brief introduction to Higgs pair decay	55
8.2	Data and simulation samples	55
9	Conclusion	61
	Appendix	63
A	Beyond the Standard Model theories	63
A.1	Supersymmetry	63
A.2	The two-Higgs-doublet model (2HDM)	63
A.3	Extra dimensions	64
A.4	Leptoquarks	66
	Auxiliary material	76
B	Efficiency Histograms (Legacy)	76

C	Visible Variables Histograms	84
C.1	EFVsTruth	84
C.2	Truth Efficiency	87
D	DiTau Histograms	88
E	χ^2 Square Test	90
F	Non-resonant $b\bar{b}\tau_{lep}\tau_{had}$ CxAOD Histograms	92
F.1	Single Lepton Trigger (SLT)	92
F.2	Lepton Tau Trigger (LTT)	95
G	HepData material	98
G.1	Samples legacy & master trigger tau code	98
G.2	Signal & background samples for Higgs pair production in the $b\bar{b}\tau\tau$ channel.	98
G.3	Trigger Menu 2021	99

1 Introduction

The Standard Model (SM) theory represents our best understanding of the fundamental particles in physics. Initially it is began to write in the early 1970's, it is a self-consistent theory which has demonstrated huge successes in providing experimental predictions that they have been confirmed by the observations over time. In 2012, The discovery of a particle similar to the theoretically predicted SM Higgs boson, by ATLAS and CMS experiments at the Large Hadron Collider (LHC) was a important the experimental test of the SM. Now, precise measurements of the Higgs boson coupling are important to test the validity of the Brout-Englert-Higgs mechanism, the electroweak theory and the SM theory itself, as well as all the coupling are predicted by the SM theory, given the measured values of the masses of the particles and of the vacuum expectation value. From a general perspective, much effort is put into controlling the shape of the Higgs potential. The direct way to measure this coupling is studying the Higgs Boson pair production process. In the SM, Higgs boson pairs can be produced at the LHC via gluon-gluon fusion (ggF) through top-quark loops and the triple Higgs-self interaction, thus the study of this process can allow one to measure the coupling λ_{HHH} and probe the structure of the Higgs potential. The SM cross section for Higgs pair production at the LHC via ggF with pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ [TeV] is $\sigma = 33.41$ [fb] [1–4], three orders of magnitude smaller than the single Higgs boson production cross section. The observation of this process and the Higgs self-coupling value is thus particularly challenging because of its small cross section and it is one of the main goals for the High Luminosity LHC (HL-LHC).

Although all experimental measurements are in agreement with the SM, this is a incomplete theory as there are phenomena in nature that it cannot explain. More theories beyond the Standard Model (BSM) have been developed trying to answer the cracks in SM theory. The presence of new diagrams with new vertices, or Modifications to the top-quark Yukawa coupling or the Higgs self-coupling, could enhance the di-Higgs production rate and modify the kinematic properties of the process showing hints of possible new physics BSM in the non-resonant di-Higgs production. In addition, others BSM theories predict heavy resonances that could decay into a pair of Higgs bosons, would also manifest in a modification in a modification of the di-Higgs production rate and kinematic as resonant production rate and kinematic as resonant production.

It is nevertheless important to continue exploring di-Higgs production with the increase of the centre-of-mass energy and luminosity in all the LHC Runs to develop improved analysis techniques and to test the presence of new physics BSM that might enhance the production rate. This document contributes in this sense.

This thesis presents the results of the research conducted for the ATLAS experiment [5]. It is divided into three parts. The first section provides an overview of the field of particle physics, including relevant aspects necessary to understand the experiment and the results described. In the second part, the work related to the Qualification Task is presented, focusing on the Offline Tau trigger monitoring Code, which is a crucial phase for obtaining high-quality tau candidates used in subsequent analyses. The third part showcases the work carried out in the context of Higgs studies, specifically the production of non-resonant pairs of Higgs bosons in the $bb\tau\tau$ decay channel. This includes the generation of new Sherpa samples with the calibrated xAOD format dataset (CxAOD).

The first section is divided into three subsections. The first subsection (1.1) discusses aspects of the Standard Model (SM) of particle physics. It provides a concise historical introduction and covers key concepts of gauge theories and spontaneous symmetry breaking, which are the foundations of the Standard

Model. The second subsection (1.2) focuses on the non-resonant Higgs boson pair production (HH) in the $b\bar{b}\tau\tau$ final state.

1.1 The Standard Model

1.1.1 History of particle physics

The history of the particle physics begin with the discover of the electron at 1897 by J. J. Thomson, who in his experimental work with cathode rays showed that they were composed of the charge particles [6]. This happened in the time of the atomic theory, which is inspired by the idea that all matter in the universe can be divided up only to a certain point, thus emerging the concept of 'atom' (from Greek, meaning indivisible), whose elements combined form the well-know periodic table. This culminated in the Rutherford-Bohr model of the atom in 1913, which proposes in addition to electrons to include protons as a fundamental particle [7].

The important fact that atom had internal composition meant they were not truly indivisible. Other hint of this hypothesis was the electron size, 1800 times smaller than the smallest atom (hydrogen), so the term elementary particle was eventually coined to represent truly indivisible particles. In later times, about 1930, new particles were being constantly discovered in reactors, through cosmic rays, and especially with the advent of particle accelerators [8].

Later, in the 1950's the variety of know particles was so large that it was becoming obvious that these could not all be fundamental, but rather the combination of smaller set of truly fundamental particles, which could explain this ever increasing *particle zoo*.

The work by Murray Gell-Mann and George Zweig, which the quark model was proposed, posits that the hundred of observed mesons and baryons stemmed from only 3 fundamental quarks (and their antiparticles), up, down and strange. Today, we also know of the existence of three more, charm, bottom and top, we call all of these varieties flavors of quarks. Quarks also possess a quantum number referred to as color; single quarks cannot be observed due to *color confinement*, only bound states of states of quark-antiquark pair (known as a *mesons*) or three quarks (or three antiquark, known as *baryons*) of different color may be observed as real particles.

Moreover, there are another set of particles called *leptons*, those already known electron, muon and τ particles, with three additional neutral leptons called neutrinos (one for each *flavor*) complete the fundamental particles named *fermions*, with semi-integer spin, same as quarks. See Figure 1.

while the fundamental particles constituting matter were discovered, the development fields theories were constructed to explain their interactions in the context of *fundamental interactions (or forces)*¹. In the course of time, the most successful quantum field theories proved to be *gauge* theories, in which so called gauge *boson* act as mediators of the interaction, their existence stemming from internal symmetry of the system, and is formally described by group theory, as it will show in next sections. Also, we will briefly describe the Brout-Englert-Higgs mechanism [9, 10], when a new scalar field known as a Higgs field allows the gauge boson to acquire mass via spontaneous symmetry breaking. The Higgs field would also be responsible for the masses of the quarks and charged leptons via Yukawa coupling, and the existence of a new scalar particle known as the Higgs boson was predicted. A particle with such characteristics was

¹ gravitation, part of one of these fundamental forces, remains unexplained in terms of the renormalizable quantum field theories and this is not cover in the SM.

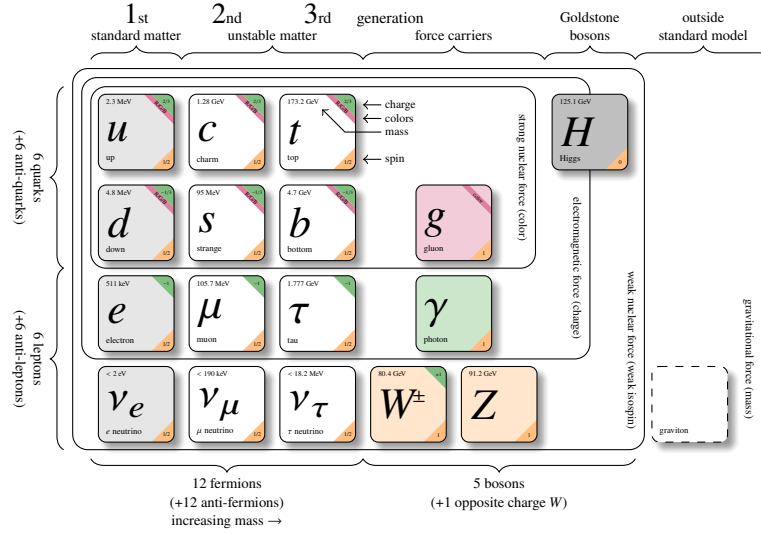


Figure 1: Fundamental particles of the Standard Model (SM).

found by the ATLAS [11] and CMS [12] experiments at LHC in 2012, validating the theory almost 50 years after it was conceived.

1.2 The Standard Model and the Higgs Boson

So far, the theory that describes the matter in the entire universe is the Standard Model. Everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our best efforts are put into understanding how these particles and three of these forces interact compiled in this theory of particles physics. From the beginning of the SM, many experiments it has become established as a well-tested physics theory that explain all experimental result. One of the main results is the Higgs boson. The existence of this particle was predicted by the SM and it was only missing piece in the experimental observation until the discovery of a boson in 2012 [11, 12], whose properties are very consistent with the SM Higgs boson. Although this does not say that the theory is complete, as a part of a theory of nature.

This chapter introduces the basic concepts of the SM theory, describes the SM gauge theory and the three fundamental forces included in it and explains the Brout-Englert-Higgs mechanism and the role of the Higgs boson. Finally, the properties of the Higgs boson and the crucial role played by the Higgs boson pair production process in the Higgs self-coupling measurement.

1.2.1 Main concepts

The two basic types of fundamental particles that constitute the building blocks of the matter are called leptons and quarks. Each group consist of six particles organized in pairs (called "generations"), having the same properties except the mass. The quarks are all electrically charged, with up-type quarks having charge $+\frac{2}{3}$ and down-type quarks $-\frac{1}{3}$ and carry a "colour" charge (R,G,B), also they are paired in three generations: the "up quark" and "down quark" form the first generation, followed by the "charm quark" and "strange quark" are part of the second generation, and the "top quark" and "bottom quark" in the third

generation. The six leptons are similarly arranged in the three generations: the highly known "electron" and the "electron neutrino", the "muon" and the "muon neutrino", and the "tau" and the "tau neutrino". discarding the neutrinos, these particles has a electric charge -1. The lightest particles make up the first generation, whereas the heavier particles belong to the other generations. The particles with the larger lifetime are part of the first generation, the stable matter, while the heavier particles of the second and third generation decay subsequently into particles of the lower generations. All the fermions has semi-integer spin (1/2). In addition, each of these particles has a corresponding anti-particle, which has the same mass, spin and lifetime properties but opposite sign of the quantum numbers related to the charges.

According to physics, the fundamental forces in the universe are: The electromagnetic force, the weak force, the strong force and the gravitational force. The first one acts between electrically charged particles. The weak interaction is responsible for phenomena like nuclear β -decays and absorption and emission of the neutrinos and it is approximately 1000 times weaker than the electromagnetic force. The gravitational force acts between massive particles and it is by far the weakest force being about 10^{38} times weaker than the electromagnetic force. The SM includes the first three forces, excluded the gravitational force. They result from the exchange of the force-carrier particles, which are boson with spin 1. Each force has its own boson: the electromagnetic force is carried by the "photon", the "W" and "Z" bosons are responsible for the weak force and the strong force is carried by the "gluon". However, the most familiar force in our everyday lives, gravity, is not part of the SM, as it is extremely difficult to combine in a single theory the quantum theory and the general theory of relativity, it means, the microscopic world with the macroscopic world. Although not yet found, the "graviton" should be the corresponding force-carrying particle of gravity. Anyhow, the effect of gravity is so weak as to be negligible at the scale of the fundamental particles, so the SM still works well despite its exclusion of one of the fundamental forces. The Higgs boson is responsible for giving the mass to the mass to the fermions and to the force-carrier boson (see Figure 1).

1.3 The Standard Model gauge theory

The Standard Model is a relativistic quantum field gauge theory, incorporating relativity and quantum mechanics, where particles are described as excitation of quantum fields and interactions are related to local gauge symmetries of the Lagrangian. Theoretically, perspective, the SM has a simple and elegant structure: it is a gauge theory based on the symmetry

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad (1)$$

where

- $SU(3)_C$ is the symmetry group of the strong interaction and the letter C refers to the letter C refers to the colour charge;
- $SU(2)_L \otimes U(1)_Y$ is the symmetry group of the electroweak interactions that unifies the weak and electromagnetic interactions, the letter L stands for left and indicates that the symmetry only involves left-handed particles and the letter Y stands for the weak hypercharge which is related to the electric charge (Q) and the weak isospin (T) by the formula $Q = T_3 + Y/2$, with T_3 being the third component of the weak isospin.

The matter particles are described by fermionic fields, with spin 1/2, and the force-carries by bosonic fields with spin 1. The dynamics is determined by an action S written in terms of a Lagrangian density $\mathcal{L}(x)$ that contains the free Lagrangian of the fields ($\Phi(x)$), which accounts for their free propagation, and additional terms that respect the above symmetries and account for their interactions:

$$S = \int d^4x \mathcal{L}(x). \quad (2)$$

The evolution of the system occurs along a path where the action is stationary

$$\partial S = \partial \int d^4x \mathcal{L}(\Phi(x), \partial\Phi(x)) = 0, \quad (3)$$

and we can use the Euler-Lagrange equations that correspond the equations of motion of the system:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi)} \right) - \frac{\partial \mathcal{L}}{\partial \Phi} = 0. \quad (4)$$

A gauge symmetry is any transformation of the field

$$\Phi(x) \rightarrow \Phi'(x) = \Phi(x) + \delta\Phi \quad (5)$$

that does not change the Lagrangian and consequently does not change the equations of motion. According to the Noether's theorem, there is a conservation law that corresponds to any continuous symmetry of the Lagrangian:

$$\partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi)} \delta\Phi = \partial_\mu J^\mu = 0 \quad (6)$$

Where J^μ is the conserved current and

$$Q = \int dx J^0 = \text{constant} \quad (7)$$

is the conserved charge associated to the symmetry.

A perturbative expansion of the action is used for cross section calculations in a certain process. Rules for calculating transition amplitudes between initial and final states can be derived from the Lagrangian. the Feynman rules, and they can be used to make perturbative calculations. They are represented by graphs in diagrams form, which fermions are represented by solid and straight lines, electroweak vector boson by sinusoidal lines, gluons by cycloid lines and the Higgs boson by dashed straight lines. Vertices where lines meet represent interactions. The number of vertices gives the order of the term in the perturbation series expansion of the transition amplitude. The lowest possible order for a given process is called Leading Order (LO). Following the rules, the transition amplitude can be derived: each internal line corresponds to a factor of the virtual particle's propagator, each vertex gives a factor derived from interaction term in the Lagrangian, and incoming and outgoing lines carry energy, momentum, and spin. In this thesis the Feynman diagrams are drawn with time running from left to right so initial states are on the left and final ones on the right.

1.3.1 Quantum electrodynamics QED

Quantum electrodynamics is the oldest relativistic quantum field theory developed. It is an abelian gauge theory describing the dynamics of the interaction of fermions with the electromagnetic field.

The Lagrangian of a free massive fermion is given by:

$$\mathcal{L}_{Dirac}(x) = \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x) \quad (8)$$

where $\psi(x)$ is the fermion field, γ^μ are the Dirac matrices and m is the mass of the fermion. The electrodynamic Lagrangian needs to be invariant under the local gauge transformation

$$\psi(x) \rightarrow \psi'(x) = e^{ie\alpha(x)}\psi(x) , \quad (9)$$

where $\alpha(x)$ is a function that defines the local (depending on a space-time coordinates) phase transformation that belongs to the unitary abelian symmetry group $U(1)$. In order to have the Lagrangian invariant under this transformation it is necessary to introduce a gauge field $A_\mu(x)$, which is the photon field, and transforms as

$$A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x) . \quad (10)$$

The derivative has to be replaced by the covariant derivative as follow

$$D_\mu = \partial_\mu + ieA_\mu \quad (11)$$

Where e is the electric charge of the fermion, and the Lagrangian can be written as:

$$\mathcal{L}_{QED}(x) = \bar{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x) - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x) , \quad (12)$$

Here, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor. This Lagrangian contains the kinematic terms of the free Dirac Lagrangian of the electromagnetic field and the interaction term between fermions and the electromagnetic field.

1.3.2 Quantum chromodynamics (QCD)

Quantum chromodynamics is responsible for describing the strong interactions between quark and gluons. It is a non-abelian gauge theory based in the Lie symmetry group $SU(3)_C$. The letter C indicates that the symmetry is in the colour space, where the colour red, green and blue are the charge related with the strong interaction. Quarks carry a colour charge and gluons carry a colour and an anti-colour charge. The free Lagrangian for the quarks is the Dirac Lagrangian:

$$\mathcal{L}(x) = \bar{q}(x)(i\gamma^\mu \partial_\mu - m)q(x) . \quad (13)$$

The chromodynamics Lagrangian needs to be invariant under local transformations

$$q(x) \rightarrow q'(x) = e^{i\alpha^a(x)T_a}q(x) \quad (14)$$

where $\alpha_a(x)$ is the arbitrary local of the transformation and $T_a = \frac{\lambda_a}{2}$, with $a = 1, \dots, 8$ and λ_a being the Gell-Mann matrices, are the generators of the non-abelian symmetry group $SU(3)$. The algebra is given by $[T_a, T_b] = if_{abc}T_c$, where f_{abc} are the structure constants of the group. In order to have the Lagrangian invariant under this transformation it is necessary to introduce eight fields $G_\mu^a(x)$, that are the gluon fields, and transform as

$$G_\mu^a(x) \rightarrow G_\mu'^a(x) = G_\mu^a(x) - \frac{1}{g_s}\partial_\mu\alpha_a(x) - f^{abc}\alpha_b(x)G_{c\mu}(x) . \quad (15)$$

The derivative ∂_μ has to be replaced by the covariant derivative

$$D_\mu = \partial_\mu + g_s T^a G_\mu^a , \quad (16)$$

where g_s is the strong interaction coupling constant, and Lagrangian can be written as:

$$\mathcal{L}_{QCD}(x) = \bar{q}(x)(i\gamma^\mu D_\mu - m)q(x) - \frac{1}{4}G_{\mu\nu}^a(x)G_a^{\mu\nu}(x) , \quad (17)$$

Where $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc}G_{b\mu}G_{c\nu}$ is the gluon field tensor. The equation (17) contains the kinematic term of the free Dirac Lagrangian of the quarks and the free Lagrangian of the gluon fields, but also the interaction between gluons themselves. The gluon self-interaction is the main difference between the last theory and it is particular non-abelian theories. This interaction is responsible for the unique and salient feature of QCD: The interaction strength $\alpha_s = g_s^2/4\pi$ between quarks become smaller as the distance between them gets shorter (or the energy scale gets larger) as the gluon self-coupling has an anti-screening effect on the colour charge. This behaviour of α_s has two consequences:

- asymptotic freedom: at large energy scales quarks and gluons behave as free particles;
- colour confinement: quarks and gluons cannot be directly observed, only colour-neutral states can be observed, as they cannot be separated at low energy scales so they are confined into hadrons.

1.3.3 Electroweak theory

The electroweak (EW) was built in order to combine the electromagnetic and weak interactions in a unified theory in which they are two manifestations of the same interaction. The unification is accomplished under the gauge symmetry group $SU(2)_L \otimes U(1)_Y$, where L is left-handed weak isospin and Y is the hypercharge, related to the electric charge (Q) and the weak isospin (T) by the formula $Q = T_3 + Y/2$, which are the generators of the symmetry group. Fermions are organised in doublets with weak isospin $T = 1/2$ for the left-handed states and singlet with $T = 0$ for the right-handed ones:

$$\chi_L = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L, \begin{pmatrix} q^u \\ q^d \end{pmatrix}_L \quad (18)$$

$$\psi_R = l_R, q_R^u, q_R^d \quad (19)$$

with l indicating the charged leptons, ν_l the corresponding neutrinos and $q^{u,d}$ the up-type and down-type quarks. The Lagrangian for these fermions is required to be invariant under local transformations of $SU(2)_L \otimes U(1)_Y$, which transform the fields as:

$$\chi_L(x) \rightarrow \chi'_L(x) = e^{i\beta(x)Y + i\alpha^a(x)\tau_a} \chi_L(x) \quad (20)$$

$$\psi_R(x) \rightarrow \psi'_R(x) = e^{i\beta(x)Y} \psi_R(x), \quad (21)$$

where $\alpha(x)$ and $\beta(x)$ are the phase transformation factors of the local gauge $SU(2)_L$ and $U(1)_Y$ symmetry group, $a=1,2,3$ and $\tau_a = \frac{\sigma_a}{2}$ with σ_a being the Pauli matrices, are the generators of $SU(2)$. As in the last theories cases, from the free Lagrangian replaces the derivative with the covariant derivative, as follow:

$$D_\mu = \partial_\mu + igW_\mu^a\tau_a + ig'B_\mu Y, \quad (22)$$

where four gauge fields are introduced: W_μ^a , with $a = 1, 2, 3$, are the fields associated to the $SU(2)_L$ symmetry, B_μ is the field associated to the $U(1)_Y$ symmetry and the both g, g' are the respective coupling constants. The field strength tensor are:

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g\epsilon^{abc}W_{b\mu}W_{c\nu} \quad (23)$$

$$W_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (24)$$

The EW Lagrangian is:

$$\mathcal{L}_{EW}(x) = \bar{\chi}_L(x)\gamma^\mu(i\partial_\mu - g\frac{\tau_a}{2}W_\mu^a + \frac{g'}{2}B_\mu)\chi_L(x) + \bar{\psi}_R(x)\gamma^\mu(i\partial_\mu + g'B_\mu)\psi_R(x) - \frac{1}{4}W_{\mu\nu}^a(x)W_a^{\mu\nu}(x) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}. \quad (25)$$

The gauge boson are:

$$A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (26)$$

$$Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (27)$$

$$W_\mu^\pm = \frac{1}{2}(W_\mu^1 \mp W_\mu^2), \quad (28)$$

where θ_W is the Weinberg angle defined in terms of the coupling constants g and g' through:

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad \cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}, \quad (29)$$

then, the electric charge is

$$e = g \sin \theta_W = g' \cos \theta'^2 \quad (30)$$

However, this Lagrangian describes the interaction between massless fermion fields and massless gauge fields. This is in contrast with the experimental observations of massive fermions and massive bosons, but adding mass terms would violate the gauge invariance.

1.3.4 Brout-Englert-Higgs mechanism

The solution of the problem that the last paragraph point out is part of this section. In 1964, three physics provided a model, to solve the mass problem for boson and fermions preserving the gauge invariance. This model introduces an additional field, the Higgs field, with the mechanism of the electroweak symmetry breaking which gives rise to massive gauge bosons².

A complex scalar field in the form of a doublet of $SU(2)$ with $Y = 1$ is introduced:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (31)$$

Its Lagrangian can be written in terms of kinematic and potential term as:

$$\mathcal{L}_{Higgs}(x) = (D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi) \quad (32)$$

where D_μ is the covariant derivative of $SU(2)_L \otimes U(1)_L$

$$D_\mu = \partial_\mu + igW_\mu^a \tau_a + ig' B_\mu Y, \quad (33)$$

and $V(\Phi)$ is the potential given by

$$V(\Phi) = \mu^2 \Phi \Phi^\dagger + \lambda (\Phi \Phi^\dagger)^2 = \mu^2 \Phi^2 + \lambda \Phi^4, \quad (34)$$

with μ and λ being free parameters. This potential is symmetric under $SU(2) \otimes U(1)$ so the symmetry of the Lagrangian is preserved.

In order to have a stable theory has to be inferiorly bounded so it has to have $\lambda > 0$, while the sign of μ^2 is not determined. The minimum of the potential represents the vacuum state and the value of the field in the minimum of the potential gives the vacuum expectation value (vev) of the Higgs field $\langle \Phi \rangle \equiv v$. The vacuum expectation value of the Higgs field is the crucial quantity for the symmetry breaking and the Higgs mechanism. There are two possible scenarios depending on the sign of μ^2 :

- $\mu^2 \geq 0$: the potential has a parabolic shape with a single minimum at $\Phi_0 = \langle \Phi \rangle \equiv v = 0$ and the ground state is symmetric under transformations of $SU(2) \otimes U(1)$:

² Mass terms for the fermions are introduced as well by introducing a gauge invariant interaction between the Higgs field and the fermions, i.e. the Yukawa interaction.

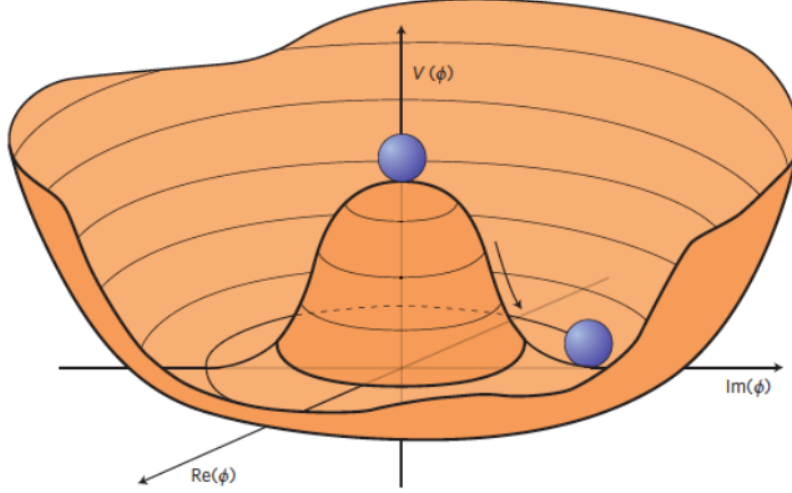


Figure 2: Illustration of the Higgs potential [13].

- $\mu^2 < 0$: the potential has the shape shown in Figure 2 where $\Phi = 0$ corresponds to a local maximum rather than a minimum and there are degenerate minima corresponding to a circumference with radius

$$|\Phi_0| = \langle \Phi \rangle \equiv v = \sqrt{\frac{-\mu^2}{2\lambda}}. \quad (35)$$

In this second case, there are multiple states with the same vacuum energy. Although the potential is symmetric, the ground state are asymmetric: transformations of $SU(2) \otimes U(1)$ applied to one of the vacuum states will rotate it to a different orientation that describes different physical states, so the symmetry is spontaneously broken. A particular ground state can be chosen with $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3 = v$:

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (36)$$

The τ_1, τ_2 generators of $SU(2)$ mix the top and bottom components of the spinor, while τ_3 rotations of an angle θ only multiply them by an opposite phase that can be removed by a $U(1)$ rotation of $\theta/2$. Thus, under both a $SU(2)$ τ_3 - rotation of θ and a $U(1)$ rotation of $\theta/2$ the vacuum is invariant. This combination of generators is $Q = \tau_3 + Y/2$, which is the electric charge, corresponds to the unbroken part of the gauge group, the $U(1)_{em}$ symmetry group. After the spontaneous symmetry breaking, three of the four degrees of freedom of the symmetry group are broken and give mass to the three gauge boson $Z, W^\pm$, while one degree of freedom is unbroken and leaves one massless gauge boson, the photon. The electroweak symmetry group is thus broken with the pattern.

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em} \quad (37)$$

This can be seen in the Lagrangian by expanding the potential around the ground state. The field $\Phi(x)$ can be written in terms of $SU(2)$ transformations adding four scalar fields $\theta_1, \theta_2, \theta_3$ and h , which parameterise fluctuations around the minimum:

$$\Phi(x) = e^{i\tau^a \theta_a / \nu} \begin{pmatrix} 0 \\ \frac{\nu+h}{2} \end{pmatrix} \simeq \frac{1}{\sqrt{2}} \begin{pmatrix} \theta_2 + i\theta_1 \\ \nu + h - i\theta_2 \end{pmatrix} . \quad (38)$$

Here, $\theta_1, \theta_2, \theta_3$ are called the massless Goldstone boson, they are generated by electroweak symmetry breaking and they can be removed from the Lagrangian by doing a $SU(2)$ gauge transformation so that the resulting field, in the so called unitary gauge, can be written as:

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix} \quad (39)$$

where $h(x)$ is the Higgs scalar field.

The Lagrangian becomes:

$$\mathcal{L}_{Higgs}(x) = \frac{1}{2}(\partial_\mu h)^2 + [m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu] \left(1 + \frac{h}{\nu}\right)^2 - \lambda \nu^2 h^2 - \lambda \nu h^3 - \frac{1}{4} \lambda h^4 \quad (40)$$

The degrees of freedom carried by the massless Goldstone boson are transferred to the massive $W^\pm$ and Z boson. All boson mass term can now be identified by looking at the terms which are quadratic in fields:

$$m_h = \sqrt{2\lambda} \nu \quad (41)$$

$$m_W = \frac{g\nu}{2} \quad (42)$$

$$m_Z = \frac{1}{2} \nu \sqrt{g^2 + g'^2} = \frac{m_W}{\cos \theta_W} . \quad (43)$$

In addition, the Lagrangian contains triple and quartic coupling terms of the field h with the heavy gauge boson $W^\pm$ and Z , which are proportional to the mass squared of the gauge boson, $\lambda_{VVH} = \frac{2m_V^2}{\nu}$ and $\lambda_{VVHH} = \frac{m_V^2}{\nu^2}$ respectively, and triple and quartic Higgs boson self-coupling which are proportional to the Higgs mass squared:

$$\lambda_{HHH} = \lambda_\nu = \frac{m_h^2}{2\nu} \quad (44)$$

$$\lambda_{HHHH} = \frac{\lambda}{4} = \frac{m_h^2}{8\nu^2} . \quad (45)$$

The scale of the boson masses and of the coupling is given by the value of the vev, ν . It can be evaluated using the empirical value of the Fermi constant G_F from the muon decay, as $\frac{G_F}{\sqrt{s}} = \frac{g^2}{8M_W^2}$, so the vacuum expectation value be written as:

$$\nu = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246 \text{ [GeV]} . \quad (46)$$

Nevertheless, the Higgs boson mass m_h and the masses of the vector boson be predicted as λ and g, g' are free parameters of the theory. Precise measurements of the boson masses and of their coupling to the Higgs boson are important to test the validity of the Brout-Englert-Higgs mechanism, the electroweak theory and the SM theory itself.

1.3.5 Yukawa coupling and fermions masses

Similar to the showed in the previous section for vector bosons, the Yukawa coupling aims to explain why fermions have mass. Adding directly mass term for the fermions would break the gauge invariance of the Lagrangian, but a new invariant interaction term between fermions and the Higgs field, called the Yukawa term, can be added assuming that fermions acquire their masses from interactions with the Higgs field like the vector boson do. For the leptons:

$$\mathcal{L}_{Leptons}(x) = -y_l(\bar{\chi}_L\phi\psi_R + \bar{\psi}_R\phi^*\psi_L) , \quad (47)$$

where y_l are free parameters for $l = e, \mu, \tau$. Using the parameterization of the Higgs field of Equation 39 the term becomes:

$$\mathcal{L}_{Leptons}(x) = \frac{-y_l v}{\sqrt{2}}(\bar{l}_L l_R + \bar{l}_R l_L) - \frac{y_l}{\sqrt{2}}(\bar{l}_L l_R + \bar{l}_R l_L)h = -m_l \bar{l}l - \frac{m_l}{v}\bar{l}lh , \quad (48)$$

with the lepton masses given by $m_l = \frac{-y_l v}{\sqrt{2}}$. This term of the Lagrangian contains the kinematic term of the massive leptons and the interaction term of the leptons with the Higgs field, with a Yukawa-coupling that is proportional to the mass of the fermion, $y_l = \frac{m_l \sqrt{2}}{v}$. Since there are no right-handed neutrinos in the SM, the left-handed ones need to be massless.

The mass terms for the quarks follow in a similar way. Now, with quarks there are also right-handed down-type quarks, both components of the doublet are massive. In order to built the upper component in the doublet its conjugate is needed:

$$\Phi_C = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix} . \quad (49)$$

Using this, the term of the Lagrangian fro the quarks is:

$$\mathcal{L}_{Quarks}(x) = -y_d^{ij}(\bar{u}_i, \bar{d}_i)_L \Phi d_{jR} - y_u^{ij}(\bar{u}_i, \bar{d}_i)_L \Phi_C u_{jR} + h.c. , \quad (50)$$

where y_q^{ij} are matrices for the quark families i, j and up and down down-type quarks q . This Yukawa coupling matrices can be diagonalised if the left-handed quark fields are rotated by a unitary transformation, $u_L^i \rightarrow u_L'^i = U_u^{ij} u_L^j$ and $d_L^i \rightarrow d_L'^i = U_d^{ij} d_L^j$, where $V_{CKM} = U_u^\dagger U_d$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Finally, the Lagrangian in the diagonal form and the unitary gauge is:

$$\mathcal{L}_{Quarks}(x) = -m_d^i \bar{d}_i d_i (1 + \frac{h}{v}) - m_u^i \bar{u}_i u_i (1 + \frac{h}{v}) , \quad (51)$$

where the again the fermion masses are given by $m_f = \frac{-y_f v}{\sqrt{2}}$ and it can be seen that the Yukawa-coupling between the fermion and Higgs boson is proportional to the mass of the fermion $y_f = \frac{m_f \sqrt{2}}{v}$. The Yukawa-couplings are free parameters of the theory and so are the fermion masses. The Yukawa interaction between fermions and the Higgs boson gives mass to the fermions through a mechanism which is different from the one that gives mass to the vector boson. Precise measurements of the Yukawa coupling are needed to test the validity of this mechanism.

1.4 The Higgs boson and Higgs pair production

The Higgs boson is predicted for the Brout-Englert-Higgs mechanism in the SM theory as described in section 1.3.4. The last missing particle of the SM theory was observed using pp collisions data recorded by the ATLAS and CMS experiments at the LHC at a centre-of-mass energy of $\sqrt{s} = 7$ [TeV] in 2011 and $\sqrt{s} = 8$ [TeV] in 2012 [11, 12].

After the discovery, the properties of the new particle need to be studied in order to determinate if all of them are in agreement with the prediction for the SM Higgs boson. To date, its mass has been measured [14] from the combination of the ATLAS and CMS result in the four leptons final state to be

$$m_H = 125.09 \pm 0.24(0.21_{stat} \pm 0.11_{syst}) [GeV] , \quad (52)$$

and studies on the spin and parity quantum numbers show that the particle is compatible with the SM neutral spin-0 boson with $J^P = 0^+$ [15]. Also, it was proven that it couples to the gauge boson and to the fermions of the third generation [16–21], with couplings being consistent with the SM predictions. However, the observed coupling need to be measured with precision in order to be compared with the expectations and check that there are indeed no deviations. Moreover, not all couplings predicted by the SM have been observed so far: couplings of the Higgs boson to fermions the first and second generations and the Higgs self-coupling are still unobserved.

1.4.1 Higgs production and decay

With the measured mass values of the vector boson and of the fermions, all their coupling to the Higgs boson are predicted by the SM theory. Therefore, all Higgs boson production and decay modes, with their cross sections and branching ratios (BR's), can be predicted given also the mass of the Higgs boson.

The main Leading Order (LO) Feynman diagrams contributing to the Higgs production are shown in Figure 3 and the corresponding branching ratio are show in figure 4 as a function of the centre-of-mass energy $m_H = 125$ [GeV]. The ggF is the production mode with the largest cross section, 48.58 [pb] at 13 [TeV], followed by the vector-boson fusion (VBF), Higgs-strahlung (VH) and associated production with a pair of top quarks (ttH). All these production modes of the Higgs boson have been observed with cross sections compatible with the SM predictions.

The Higgs decay branching ratios as a function of its mass m_H and the corresponding values for a mass of $m_H = 125.09$ [GeV] are reported in [2]. Since the Higgs boson does not couple to massless particles, like gluons and photons, it can decay into a pair of such particles only through quark triangle-loops, similarly to what happens in the ggF production, mostly populated by top-quark loops because of their high mass and the resulting large top-quark Yukawa coupling.

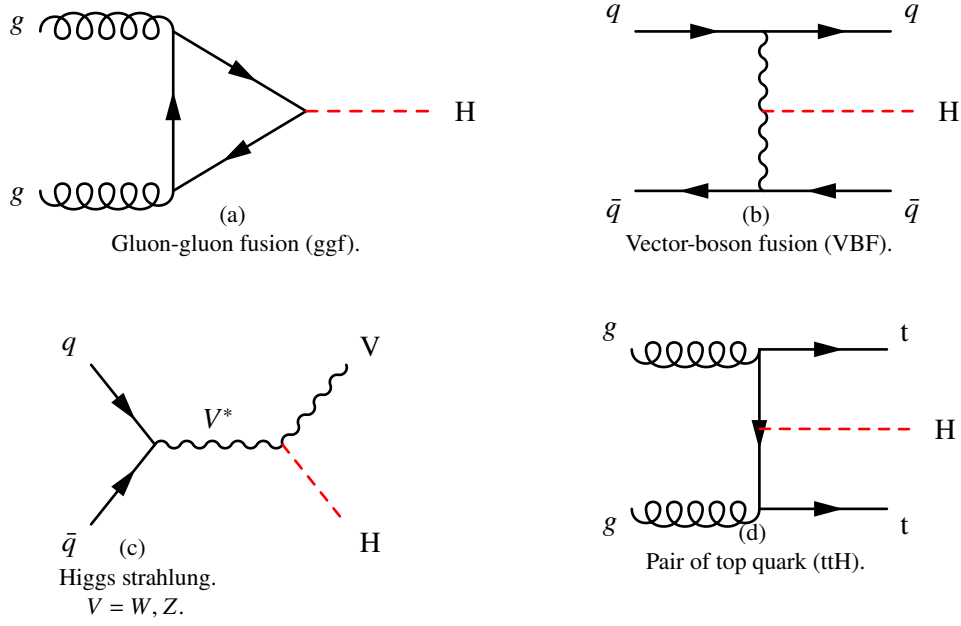


Figure 3: Main Leading Order (LO) Feynman diagrams contributing to the Higgs production [22].

1.4.2 Higgs pair production and decay

One of the important works in this thesis shown in the section 8 is an improvement in the MC samples for non-resonant Higgs boson pair production. The dominant Higgs boson pair production mode is ggF through the destructive interference of two LO diagrams shown in Figure 6 involving top-quark loops and the triple Higgs self-coupling. In the box diagram of the top-quark loops the top-quark Yukawa coupling y_t is present in two vertices so the contribution of this diagram to the amplitude is proportional to y_t^2 , while in the triangle diagram there is y_t in one vertex and the triple Higgs self-coupling λ_{HHH} in other vertex and the contribution of this diagram is proportional to the product of y_t and λ_{HHH} . Therefore, studying this process allows to directly test both the triple Higgs self-coupling and the top-quark Yukawa coupling, The SM cross section for Higgs boson pair production via ggF at $\sqrt{s} = 13$ [TeV] [1–4], calculated at Next-to-Leading (NLO), is:

$$\sigma = 33.41 \text{ [fb]}, \quad (53)$$

three orders of magnitude smaller than the single than the single Higgs production cross section. This accounts for more than 90% of the total Higgs boson pair production cross section, followed by the VBF production which is two orders of magnitude smaller, therefore only this production mode is generally considered.

For ggF Higgs bosons pair production, the cross section depends on both coupling y_t and λ_{HHH} . Considering possible modifications of them, defining effective Higgs boson coupling $k_t = y_t/y_t^{SM}$ and $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$, the amplitude of the process can be written as:

$$A(k_t, k_\lambda) = k_t^2 B + k_t k_\lambda T, \quad (54)$$

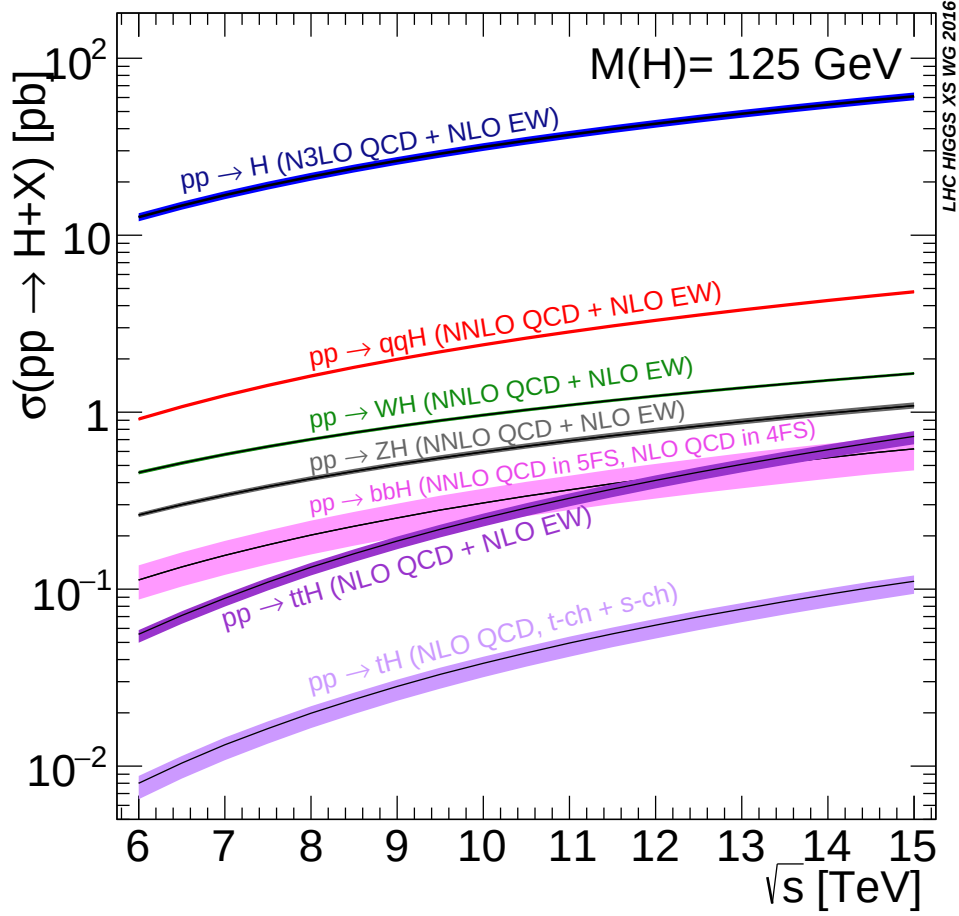


Figure 4: Standard Model boson production cross sections as a function of the centre-of-mass energy for $m_H = 125$ [GeV] [2].

B, represents the contribution of the box diagram and T the one of the triangle diagram (shown in Figure 6). The cross section can thus be expressed in term of these two new parameters as:

$$\sigma \approx k_t^4 |B|^2 + k_t^3 k_\lambda (BT + TB) + k_t^2 k_\lambda^2 |T|^2 = k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t} (BT + TB) + \left(\frac{k_\lambda}{k_t} \right)^2 |T|^2 \right]. \quad (55)$$

This shows that the overall production cross section depends on both parameters k_t and k_λ , however the kinematics only depends on their ratio k_λ/k_t that modifies the relative contribution of the two diagrams and thus the shape of the kinematic distributions³.

The di-Higgs system decay has a variety of different final states resulting from all the possible combination of the decays of the two Higgs bosons. The branching ratios for all the possible combinations of the Higgs decay channels that have been observed, assuming SM Higgs bosons with $m_H = 125.09$ [GeV] is shown in the Figure 7. The final work done in this thesis is performed in the $b\bar{b}\tau^+\tau^-$ final state, where one Higgs

³ The results of these couplings will be ignored since it is not the focus of this thesis. But it can be checked in these references [23, 24]

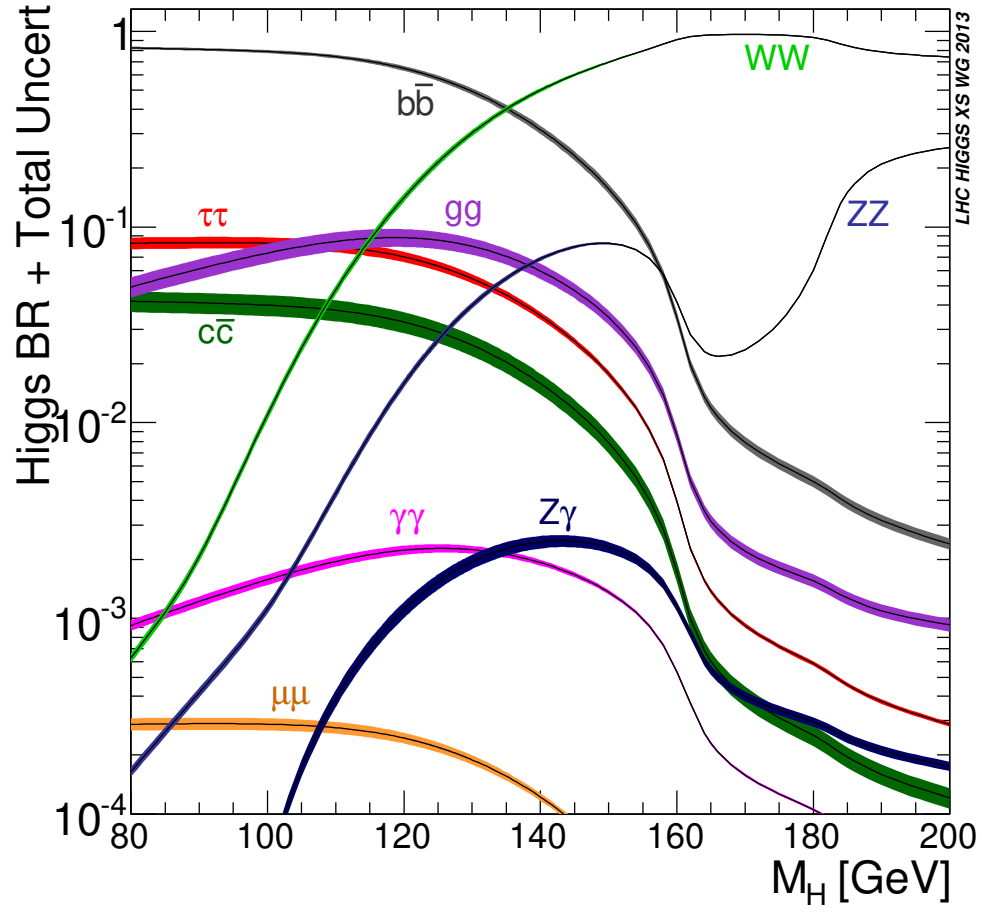


Figure 5: Standard Model boson production cross sections as a function of the Higgs Mass m_H [2].

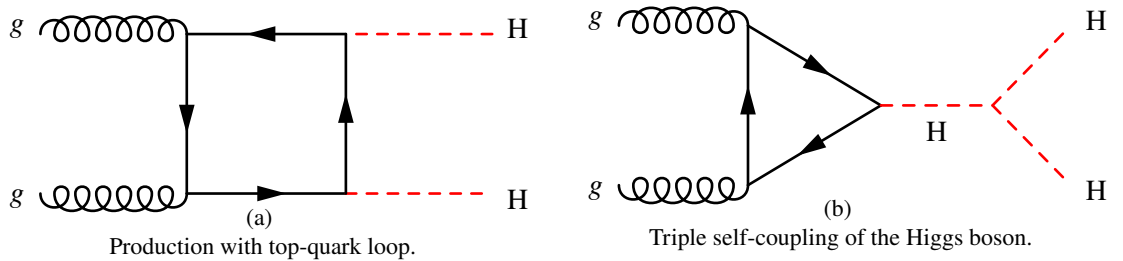


Figure 6: Leading Order (LO) Feynman diagrams contributing to ggF Higgs boson pair production [22].

boson decays to a b -quark pair and the other to a τ -lepton pair, which has the third largest observable BR corresponding to 7.4 %. The contribution of this thesis is on the final state with one τ -leptons decaying hadronically and the other one decaying less heavy lepton, $b\bar{b}\tau_{had}\tau_{lep}$.

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%	0.10%	0.029%	0.013%	0.0005%

Figure 7: Di-Higgs system decay branching ratios assuming SM Higgs bosons with $m_H = 125.09$ [GeV].

1.5 Beyond The Standard Model

As a brief mention, it could say that the Beyond standard model (BSM) tries to describe the phenomenons the SM theory does not (see Appendix A). Moreover, the SM theory also has some issues in its theoretical and mathematical framework as some features are included in the theory in an ad hoc way. It is therefore believed that the SM could be extended to a more complete and natural theory. Many BSM theories have been developed, which try to include the phenomena not explained in the SM theory and solve some of the theoretical SM issues. Some of the BSM theories under analysis in ATLAS are:

- Supersymmetry
 - The two-Higgs-doublet model (2HDM)
- Extra dimensions
 - Randall-Sundrum model
- Leptoquarks

1.5.1 Phenomena not explained

There are several physics phenomena that are observed in nature but are not explained by the SM theory. Among them, there are:

- Gravity: the SM does not include a unified description of all the four fundamental forces. The gravitational interaction described by the general relativity theory, is not included. This indicates that the SM breaks down at the gravitational scale $O(10^{19} \text{ [GeV]})$. A quantisation of the gravitational theory is needed and a new quantum field theory that can include it is required at the Planck scale.
- Dark matter and dark energy: cosmological and astrophysical observations show that the directly observable SM matter is only 5% of the energy of the universe and that there has to be another 95% made dark matter and dark energy.
- Matter-antimatter asymmetry: the universe is made of mostly matter. Assuming that matter and antimatter were produced in equal amounts during the Big Bang, the observed amount of CP-violation is not sufficient to explain the asymmetry.
- Neutrino masses: in the SM neutrinos are massless, but the observation of the neutrinos oscillations implies that they have a non-zero mass. Mass terms for the neutrinos can be added to the SM by hand, but these lead to new theoretical problems as the mechanism through which they acquire mass is not determined.
- Anomalies in the B-meson decay: several experiments (Belle, Babar and LHCb) have observed anomalies in the ratio of the decay of B-mesons to τ -leptons or muons predicted by the SM lepton universality [25, 26]. None of the observed deviations is statistically significant to claim a discovery, but they all point in the same direction, giving a potential sign of the lepton universality violation and thus something amiss in the theory.

1.5.2 Theoretical problems

In the theoretical and mathematical formulation of the Standard Model some features are included in the theory in an ad hoc way or finely tuned. This is not a real problem of the theory, as the description of the observed phenomena works fine these, but shows a lack of understanding and suggests that there could be a more fundamental theory.

- Number of free parameters: the SM theory has 18 free parameters (9 fermions, 3 gauge coupling of the fundamental interactions, 3 CKM mixing angles and 1 CP-violating phase, the Higgs mass and the Higgs vacuum expectation value) that need to be determined from experiments in order to have prediction of the dynamics defined.
- Hierarchy problem (naturalness): the Higgs mass is much smaller than the Planck mass $O(10^{19} \text{ [GeV]})$. The mass of the Higgs boson receives quantum corrections proportional to the square of the scale at which the SM breaks down, which is to our knowledge at latest the gravitational scale, implying quantum corrections $O((10^{19} \text{ [GeV]})^2)$. These very large corrections need to be precisely canceled out to leave the observed Higgs mass of $m_H = 125 \text{ [GeV]}$. This cancellation requires a high level of fine-tuning (much higher than for the logarithmically divergent quantum corrections appearing in QED and QCD) and it is therefore considered unnatural.

- Unification: the unified description of the three fundamental forces included in the SM model describes them under the symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, which is given by the direct product of three symmetry groups with three different gauge coupling constants. The coupling constants run with the energy scale and unification under one symmetry group with one coupling constant, known as Grand Unification Theory (GUT), would be possible at high energy scale if the three constants converge at one point. However, extrapolations of the gauge coupling experimental measurements show that the three coupling constants get closer but do not precisely meet in one point at the energy scale $O(10^{16} [GeV])$

2 ATLAS detector

The European Organization for Nuclear Research (CERN) is one of the largest centres for scientific research in the world, where the world's largest and most complex scientific instrument are employed to study the basic constituents of the matter and probe the fundamental structure of the universe. The CERN laboratory sits at the French-Swiss border near Geneva. It was founded in 1954 to create an European scientific centre of excellence.

The instruments used at CERN are particle accelerator and detectors. A system of several accelerators boost beams of particles (protons and ions) to high energies before the beams are made to collide with each other in the Large Hadron Collider (LHC). Detectors observe and record the products of these collisions. One of these detectors is the ATLAS (A Toroidal LHC ApparatuS) experiment [5], whose data are used in this thesis.

This chapter introduces the Large Hadron Collider accelerator, provides a short description of pp collisions physics and gives an overview of the Monte Carlo simulations used in ATLAS. Then, it provides a short description of the ATLAS experiment, where the detector components that allow one to trigger on and collect data events needed for physics analyses are described. For more information you can find it in the references [5, 27, 28].

2.1 The Large Hadron Collider

The Large Hadron Collider [29] at CERN is the highest energy collider ever built, dedicated to accelerating and colliding protons and ions. It was designed to provide proton-proton (pp) collisions with a centre of mass energy of 14 [TeV] and an instantaneous luminosity of $10^{34} [cm^{-2}s^{-1}]$, and lead ion collisions at a centre-of-mass energy of 2.76 [TeV] per nucleon and an instantaneous luminosity of $10^{27} [cm^{-2}s^{-1}]$.

To reach such high energies a system of several accelerators is used as injector chain to the LHC, as illustrated in Figure 8. The proton source is a hydrogen bottle from which protons are extracted using electric fields and the injected into the first accelerator. Each machine boosts the protons up to a certain energy before injecting them into the next one, until they reach the LHC with an initial energy of 450 [GeV]. The rotating proton beams of the LHC, once accelerated to the designed energy, collide in four interaction points, where four particle detectors have been built in order to analyse the products of the high-energy collisions.

Data recorded by the ATLAS detector [5] are used in this thesis. The other three detectors are CMS (Compact Muon Solenoid) [30], ALICE (A Large Ion Collider Experiment) [31] and LHCb (b stands for

beauty) [32]. ATLAS and CMS are both general purpose detectors built with the goal to search for the SM Higgs boson and study its properties, to make SM precision measurements and to look for possible new physics beyond the SM. ALICE is a detector built to record and analyse the heavy ions collisions products in order to study the phenomenology of the strong interaction. LHCb is a detector dedicated to B-meson physics and flavour physics in general, investigating CP violation, lepton universality and lepton flavour violation. In addition, there are smaller experiments, such as TOTEM [33] and LHCf [34], installed at some distance from the interaction points to study the production of particles in the forward region (along the beam direction).

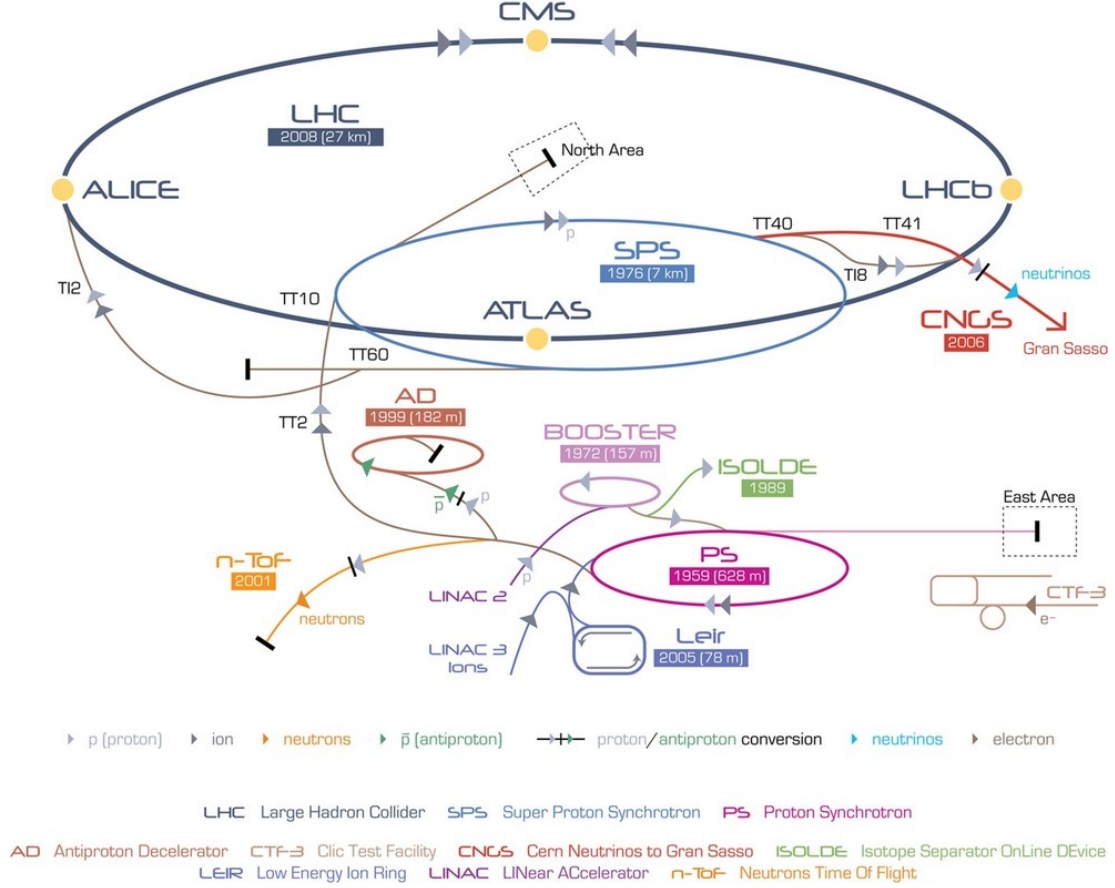


Figure 8: The layout of the LHC and the CERN accelerator complex acting as the injector chain for the LHC.

2.1.1 Machine design

The LHC is a 27 [Km] long circular hadron collider housed in the tunnel built between 1984 and 1989 for the LEP (Large Electron-Positron) collider. The tunnel is located between 45 [m] and 170 [m] below the ground surface, between the Jura mountains and the Geneva airport.

With the Run 2 data, proton beams are injected from the CERN accelerator system into the LHC in a series of bunches of 1.15×10^{11} protons, and every beam is designed to have 2808 circulating proton bunches. The bunches are arranged in "trains" of 72 bunches, with 25 [ns] spacing within the train, and 12 empty bunches between two trains. In the LHC, the proton beams are accelerated by radio frequency (RF) cavities

and they are bent around the LHC ring by large magnetic fields (8.33 [T]) given dipoles. In addition to the dipoles, quadrupoles and higher order magnets are used to correct and focus the beam into the small area where collisions take place. In order to have two counter circulating proton beams along the same circumference, oppositely oriented magnetic fields are needed. A single cryogenic is employed with a very complex twin-bore design, housing both proton rings in the same cryostat.

Collisions between circulating beams occur at every "bunch crossing", resulting in a peak collision rate of 40 [MHz]. The beams are squeezed to a transverse size of $\sim 17 [\mu m]$ at the interaction point (IP) to maximise the pp collision rate. Near the IP, the two beams are kept together in a single beams stay on parallel orbits and when the beams are ready fro colliding at the interaction point, the separation is removed.

The rate at which collisions occur depends on the instantaneous luminosity $\mathcal{L}$ and the collision cross section σ , related by:

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma \quad (56)$$

The instantaneous luminosity is given by:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} F_\gamma}{4\pi\epsilon\beta^*} \quad (57)$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, F is the geometric function to account for the crossing angle between the beams, γ stands for the relativistic Lorentz factor, ϵ is the beam emittance (a measure of the uniformity of the momentum of particle in the beam) and β^* is a measure of how narrow the beam is at the interaction point. The integrated luminosity $L = \int \mathcal{L} dt$ is measure of how many collisions have occurred. The number of events occurring for a given process with a given cross section $\sigma_{process}$ corresponding to an integrated luminosity L is given by $N_{process} = L \cdot \sigma_{process}$. Since many of the interesting physics processes at the LHC have small cross section, it is important to maximise the luminosity as much as possible.

2.1.2 The LHC operation schedule

The LHC started operating in November 2009 with pp collisions at a centre of mass energy of 900 [GeV]. The centre-of-mass energy had been rising during the first year and in 2010 it was successfully increased to 7 [TeV]. During the years 2010 and 2011 the LHC continued to run at $\sqrt{s} = 7$ [TeV] and in 2012 the centre-of-energy was increase to 8 [TeV]. At the end of its first phase of operation, named Run 1, the LHC delivered 5.5 [fb^{-1}] and 22.8 [fb^{-1}] at 7 [TeV] and 8 [TeV], respectively.

The second phase of the LHC operation, named Run 2, started in 2005, after a long shutdown, with collisions at a centre-of-mass energy of 13 [TeV]. The peak instantaneous luminosity achieved was $1.38 \times 10^{34} [cm^2 s^{-1}]$, at a bunch crossing of 25 [ns]. The total luminosity delivered during the Run 2, which ended in December 2018, is 158 [fb^{-1}] and the ATLAS experiment recorded 149 [fb^{-1}], this is show in Figure 9. The data analysed in this thesis are part of the data collected by the ATLAS experiment during the Run 2, in particular during the years 2015, 2016 and 2018. Also, the section 7, Xi-square test, uses the data from data taking for Run 3. The integrated luminosity delivered delivered by the LHC and

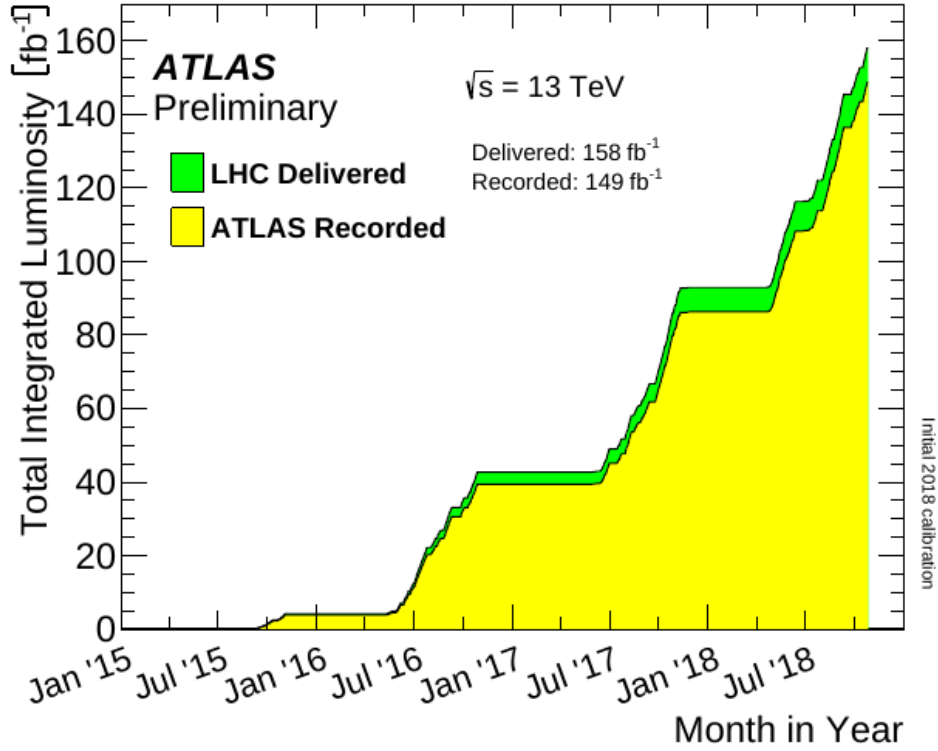


Figure 9: Integrated luminosity delivered by the LHC and recorded by the ATLAS experiment in Run 2 as a function of time [35].

recorded by the ATLAS experiment in 2015, 2016, 2018 and 2022 as a function of time is shown in Figure 10.

From 2021 the LHC starts operating in 2021 for Run 3. During the Run 3 the LHC is expected to deliver an integrated luminosity of $300 [fb^{-1}]$ from collisions at centre-of-mass energy of $14 [TeV]$. After that there will be a third long shutdown followed by a new operation period called High-Luminosity-LHC (HL-LHC), during which the instantaneous luminosity will reach $5 - 7 \times 10^{34} [cm^{-2}s^{-1}]$. The expected integrated luminosity delivered at the end of the HL-LHC is $3000 [fb^{-1}]$. The LHC operation schedule is shown in Figure 11.

2.2 Proton-proton collisions and simulation of physics processes

Proton-proton collisions are extremely complex due to the inner structure of the protons and the involvement of QCD processes. This section describes the phenomena involved in pp collisions and the simulation of the physics process happening in the collisions and inside the ATLAS detector.

2.2.1 Physics of the proton-proton collisions

The fundamental interaction in pp collisions occurs between partons, which are the quarks and gluons found inside the proton, that behave as free particles because of the QCD asymptotic freedom regime.

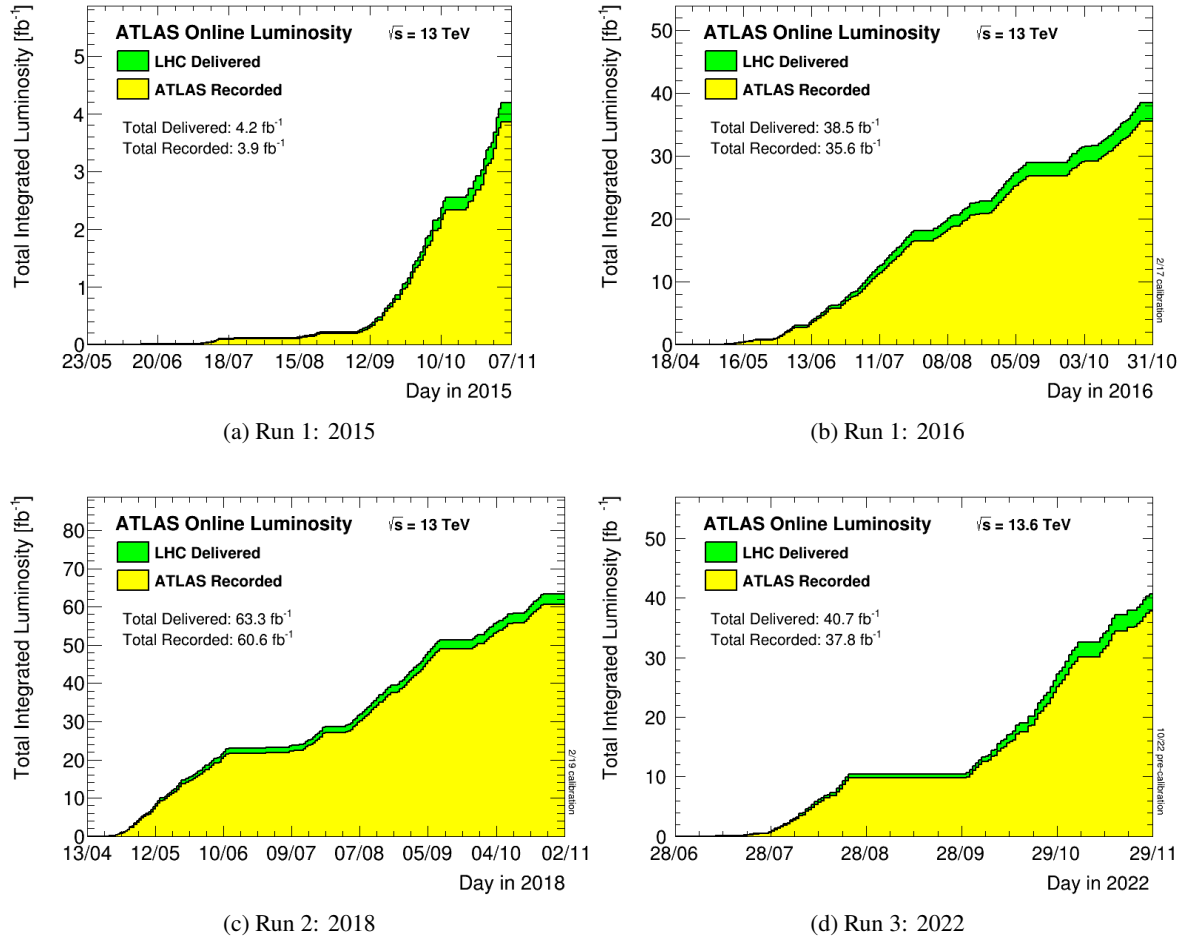


Figure 10: Integrated luminosity delivered by LHC and recorded by the ATLAS experiment in different runs [35, 36].

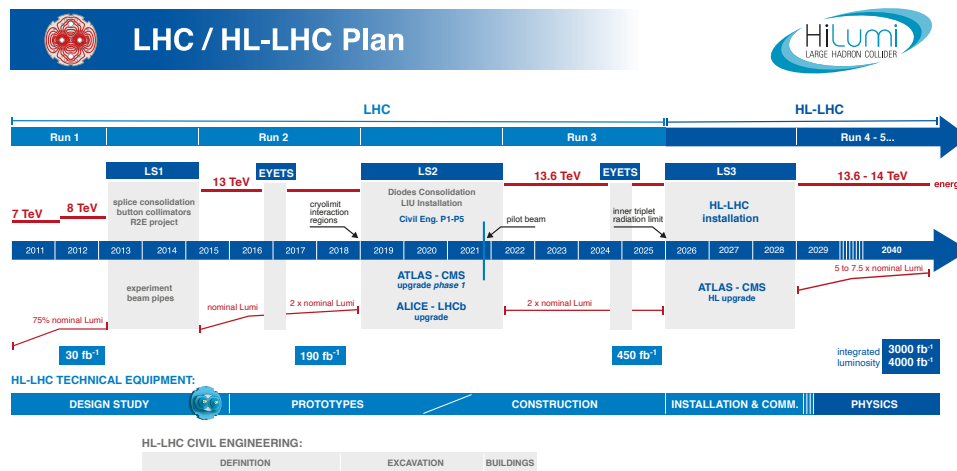


Figure 11: LHC operation schedule [37].

The proton consists of "valence quarks", one down and two up quark, which define the quantum numbers of the proton. The quarks are bound by exchanging gluons, which also take part in parton interactions. The gluons can also temporarily split into quark-antiquark pairs, the "sea quarks", that can contribute in the parton interactions as well. The partons carry a fraction of proton momentum x_i , so the actual centre-of-mass energy of the partonic interaction is:

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} , \quad (58)$$

where x_1 and x_2 correspond to momentum fractions of the interacting partons from each proton. The probability to find a parton with a certain momentum fraction x_i inside the proton is described by the parton distribution functions (PDF) [38, 39]. They depend on the the parton type and on the momentum transfer scale Q^2 of the collision. The evolution in (x, Q^2) of the PDFs is described by the "DGLAP" equation [40]. According Figure 12 that shows the PDFs for proton at $Q^2 = 10 [GeV^2]$ (left) and at $Q^2 = 10^4 [GeV^2]$, gluons dominate among all partons which means that the LHC provides a very high "parton luminosity" for gluons. For this reason LHC is sometimes called "gluon collider", where processes initiated by a gluon-gluon interaction have a much larger cross section compared to the ones initiated by quark-quark interaction.

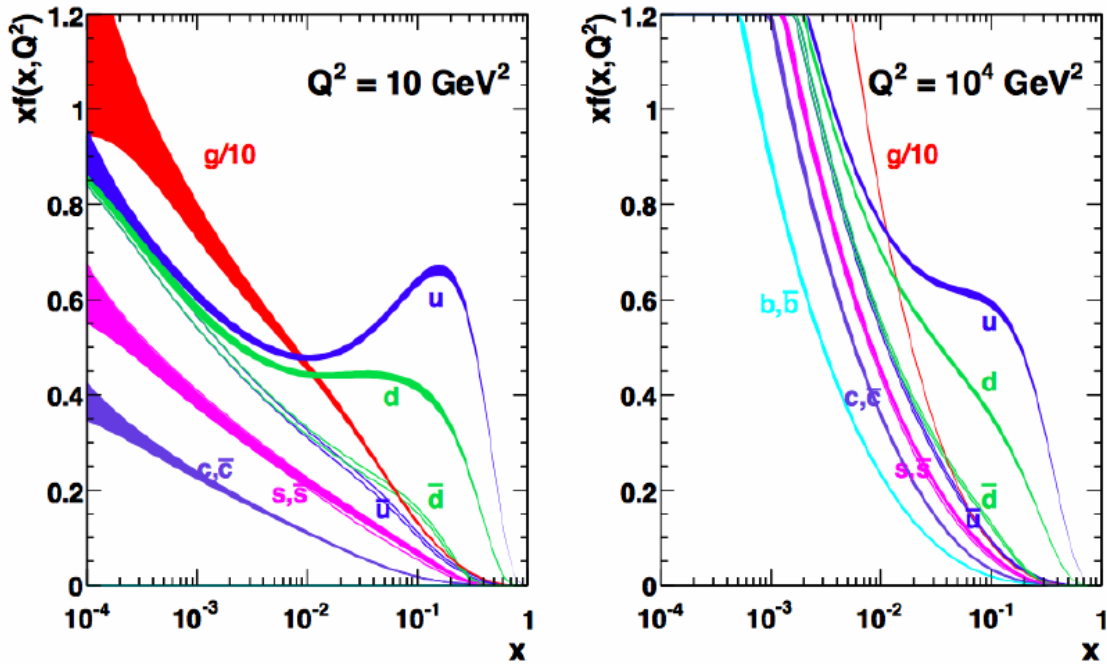


Figure 12: Parton distribution functions (PDFs) for protons at $Q^2 = 10 [GeV^2]$ (left) and at $Q^2 = 10^4 [GeV^2]$ [39].

The interactions in pp collision can be described using the "factorisation theorem" that allows one to split the description of the phenomena occurring in the collision in several parts: the incoming protons and their parton contents described by the matrix element (ME), the parton shower (PS) and hadronization of the final state partons to the colour neutral hadrons. A schematic view of the different steps is shown in Figure 13. The $pp \rightarrow X$ cross section can be thus be written as:

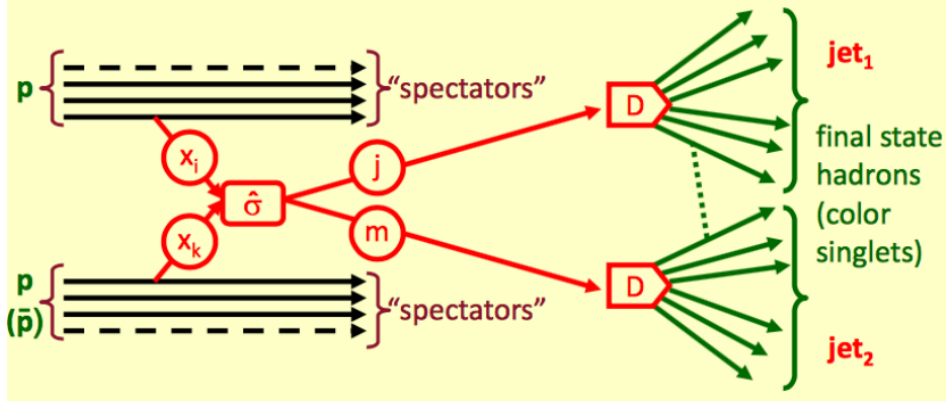


Figure 13: Schematic view of the different steps of a pp collision.

$$\sigma_{pp \rightarrow X} = \sum_{i,j} \int dx_i dx_j \int dz_k dz_m f_i(x_i, \mu_F^2) f_j(x_j, \mu_F^2) \hat{\sigma}_{i,j \rightarrow k,m}(\sqrt{s}, \alpha_s(\mu_R^2)) D_k(z_k, \mu_F^2) D_m(z_m, \mu_F^2), \quad (59)$$

where i, j are the interacting partons, $x_{i,j}$ their proton momentum fractions, $f_{i,j}$ their PDFs, $\hat{\sigma}_{i,j \rightarrow k,m}$ is the partonic cross section where k, m are the final state partons and $D_{k,m}$ are their fragmentation functions which describe the parton shower and hadronization. In these calculations, the cross section is factorised into a perturbative part, the ME, and two non-perturbative parts, the PDFs and the PS. Two energy scales need to be set: the factorisation scale μ_F and the renormalisation scale μ_R . Substructures of loops and real emissions below these scales are only approximated instead of calculated precisely in perturbative QCD calculations. The factorisation scale μ_F represents the cut-off scale between the perturbative calculation of the partonic cross section and the non-perturbative measurements of the parton density functions and fragmentation functions. The renormalisation scale μ_R represents the cut-off in the partonic cross section calculation between the finite integral and the divergent integral, which is absorbed in the running coupling constant α_s that gains a dependence on μ_R . The factorisation and renormalisation scales are an artifact of perturbation theories with divergences. The cross section does not depend on the chosen scales if all orders in perturbation theory are included in the calculations. However, as the cross sections are calculated at a fixed order in perturbation theory, not all orders are included in the calculation and hence the choice of the scale changes the prediction of the cross section. The two scales are usually set at the same value $\mu = \mu_F = \mu_R$, which is chosen to be in the order of the hard scattering scale.

2.2.2 Simulation of physics processes

In order to be able to analyse and interpret the data recorded by the ATLAS experiment, a precise comparison with the theoretical predictions is needed to quantify the agreement between the data and the Standard Model or test a possible new physics models. Monte Carlo (MC) event generators are employed to simulate events for signal and background processes. The full simulation consists in calculating the cross section of the process by evaluating the amplitudes of Feynman diagrams, generating events based on numerical MC techniques and simulating the resulting particles and their interactions with the detector material in order to predict how signal and background processes would appear in the detector.

An important aspect in the simulation of pp collision is, indeed, the possibility to factorise the different steps in the collision process. As a first step, a pp collision is simulated by using the PDFs. Then, the two partons undergo the hard interaction which is computed at a fixed order in perturbation theory, using the so-called "parton-level generators" to simulate specific processes. After the hard scattering, the parton shower and hadronization are simulated.

Moreover, the underlying event, which describes additional interactions beyond the hard scattering event and its parton shower and hadronization, needs to be simulated. These interactions are multiple parton interactions of the remaining partons in the proton that did not participate in the hard scattering. The energy scale of these additional interactions is only of the order of a few GeV , small compared to the hard scattering energy, and they produce a uniformly distributed underlying activity in the form of hadrons.

In addition, pile-up events, which are additional pp interactions in the crossing of two proton bunches, need to be simulated. They are separate collisions and are simulated separately from the hard scattering event. However, in the reconstruction of the event, they cannot be separated from the hard scattering event and therefore particles from pile-up events are part of the event signature.

A variety of MC generator programs exist. Some of these generators are so-called multi-purpose generators and can generate a full event, while some others has a more specific purpose which can only simulate the hard scattering event and have to be interfaced to one of the other generators to describe the parton shower and hadronization. After simulating the parton shower, hadronization and decay hadrons, simulated events are passed to GEANT 4 [41, 42], a software package for simulating the interactions of particles with matter. A complete model of ATLAS, including all detectors components is represented in GEANT 4. All interactions such as Bremsstrahlung, calorimeter shower, charge depositions, between others are simulated. All simulated events are then processed with the same trigger and reconstruction algorithms used for LHC collision data described next chapter 2.3.

In this document, many of these generators are used:

- MADGRAPH 5 [43]: only generates the ME at LO precision. It is used in this thesis for the simulation of the BSM di-Higgs signal processes. For the PS description it is interfaced to PYTHIA.
- MADGRAPH5_aMC@NLO [44]: only generates the ME, providing NLO precision calculations. It is used in this thesis for the simulation of the SM di-Higgs and leptoquark signal processes. For the PS description it is interfaced to HERWIG ++ or PYTHIA.
- POWHEG-BOX [45]: only generates the ME, providing NLO precision calculations for a variety of processes. It is usually interfaced to PYTHIA for the description of the PS.
- SHERPA [46]: multi-purpose generator that provides NLO precision ME calculations for a variety of processes and includes the PS. It is usually the preferred generator for processes with additional jets, which SHERPA can include in the ME calculation up to two jets.
- PYTHIA [47, 48]: It is a multi-purpose generator that provides LO ME calculations and includes the PS. Since PYTHIA only provide LO ME precision it is not always used as a stand-alone generator, but as the PS model exhibits good agreement with data it is often used to provide the PS description for other generators.
- HERWIG ++ [49]: it is a multi-purpose generator. It is not usually used as a stand.alone generator, but it is used to provide the PS description.

2.3 The ATLAS detector

ATLAS is one of two general purpose particle physics detectors at the LHC. It is designed to detect particles from both pp and ion-ion interaction. The high centre-of-mass energy and high luminosity of the pp collisions allow for the study of physics at the TeV scale. The detector has been designed to allow several types of research:

- the search for the SM Higgs boson and the measurement of its properties;
- Supersymmetry searches⁴;
- precision tests of electroweak interaction, flavour physics and QCD;
- measurement of the properties of the top quark;
- generic searches for new particles and interactions (the so-called exotic searches).

In order to deal with these challenges, ATLAS was designed to have:

- full azimuthal coverage, for missing transverse energy measurement, and large acceptance in pseudo-rapidity;
- high granularity, to operate in an environment with high particle fluxes and overlapping events;
- precision tracking, to provide high momentum resolution and to allow the reconstruction of secondary vertices to identify b-hadrons and τ -leptons;
- precise electromagnetic calorimetry, for electron and photon identification and energy measurement;
- full-coverage hadronic calorimetry, for accurate jet and missing transverse energy measurements;
- high muon identification efficiency, momentum resolution and charge determination over a wide range of momentum;
- efficient triggering on low transverse-momentum objects.

Detector Component	Design Resolution	η Coverage	
		Measurement	Level 1 Trigger
Tracking	$\sigma_{P_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	None
EM Calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic Calorimetry			
Barrel and End-Cap	$\sigma_E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
Forward	$\sigma_E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon Spectrometer	$\sigma_{P_T}/p_T = 10\%$ at $p_T = 1 [TeV]$	± 2.7	± 2.4

Table 1: Performance goal of the ATLAS detector. Unit of p_T and E are GeV [28].

In Table 1 the main performance goals of the ATLAS detector are given. Figure 14 shows a scheme of the ATLAS detector: it is the largest volume detector ever constructed for a particle collider, having the dimensions of a cylinder 44 [m] long and 25 [m] in diameter. It is longitudinally divided in three

⁴ The latest results on this topic have not been favorable to support the theory

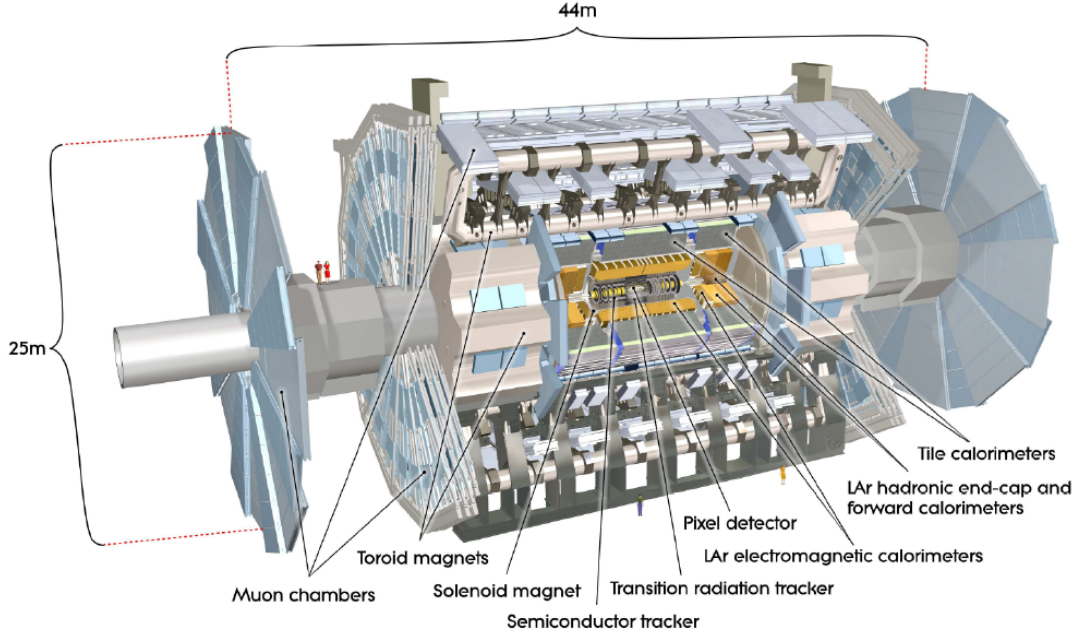


Figure 14: View of the ATLAS detector. The detectors sub-system are labelled [50].

regions: the central part named "barrel" and the two external parts named "end-caps". It consists of an inner tracking detector (ID), which is surrounded by electromagnetic calorimeters, hadronic calorimeters and a muon spectrometer. The inner detector is immersed in an axial magnetic field of 2 [T], produced by a solenoid, to allow for momentum measurement. The muon spectrometer is also immersed in a magnetic field, provided by an air-core toroid system. A two-level trigger system is used to select events to read out. The various sub-system are described in detail in the following sections.

2.3.1 Coordinate system

The ATLAS coordinate system is a right-handed Cartesian system with the located at the nominal interaction point, as illustrated in Figure 15. The z -axis lies along the beam line, the x - y plane is transverse to the beam line, with positive x pointing into the centre of the LHC ring and positive y pointing upward.

A cylindrical coordinate system is used when referring to the coordinates of a physics object in the detector. In this system, θ denotes the polar angle, r and ϕ are the radius and azimuthal angle in the x - y plane (transverse plane). The two angles, θ and ϕ , are measured, respectively, from positive z -axis and from the positive x -axis, respectively.

The energy momentum of outgoing particle, E and p , are often projected onto the transverse plane where the laws of conservation of energy and momentum can be applied as energy and momentum of the initial state are known while the initial component along the z axis is not known. The transverse momentum is then as $p_T = \sqrt{p_x^2 + p_y^2}$, and the transverse energy as $E_T = E \sin \theta$.

The θ is usually converted into the pseudo-rapidity,

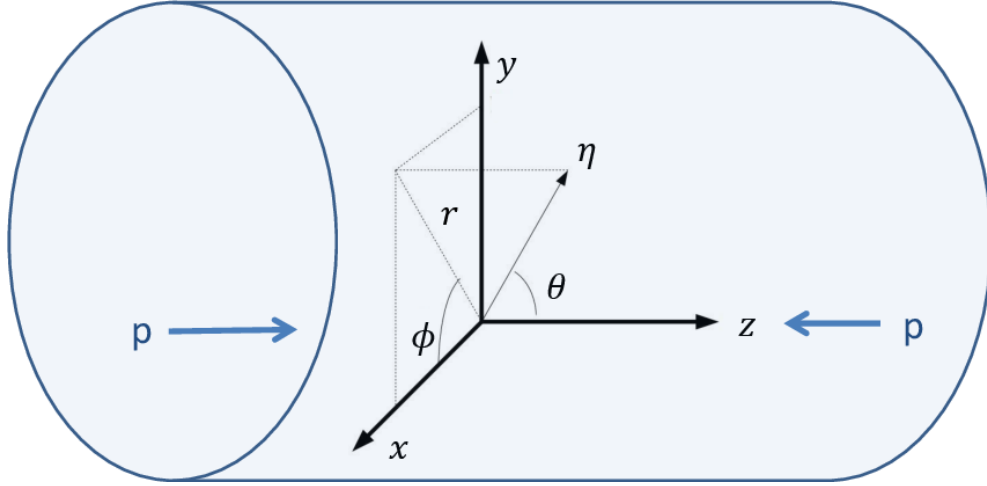


Figure 15: The coordinates system of the ATLAS detector [51].

$$\eta = -\ln \frac{\theta}{2}, \quad (60)$$

which approaches the rapidity

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}, \quad (61)$$

in the limit where $E \gg m$, with E being the energy of the particle, m its mass and p_z the longitudinal component of its momentum. The pseudo rapidity is 0 in the transverse plane and infinite along the z axis, with $\eta = 1$ at 45° from the axis. The rapidity and the pseudo-rapidity are natural variables for describing angles in a system where the initial z -momentum is known, as in hadron colliders where the interactions occur between partons from the proton, since the difference in rapidity between two particles is invariant under boosts along the z axis. A commonly used quantity is the angular distance between objects in the $\eta - \phi$ plane, defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

2.3.2 Magnets

The magnetic field is crucial for the measurement of the charge particles momentum as the momentum component of a charged track that is perpendicular to a uniform magnetic field can be estimated by measuring its bending radius R in a magnetic field B : $p[GeV] = 0.3 B[T] R[M]$. The ATLAS magnetic system [52] consists of three different types of superconducting magnets schematised in Figure 16.

The magnetic field in the inner detector is supplied by a central solenoid producing a $2[T]$ field in the z -direction. The muon spectrometer magnetic field is provided by three air-core toroid magnet: the barrel toroid and the the two end-cap toroids. The barrel toroid generates the magnetic field in the central zone of muon spectrometer, along the tangential direction of the circumferences centered on the z -axis (ϕ direction). The end-cap toroid are two smaller toroid designed to provide magnetic field in forward areas of the muon spectrometer. The magnetic field generated by the toroid has an intensity between $0.5 [T]$ and $4 [T]$. As a

result of the ATLAS magnetic system, the z and the ϕ magnetic fields bend track in the ϕ direction in the inner detector, and in the η direction in the muon spectrometer.

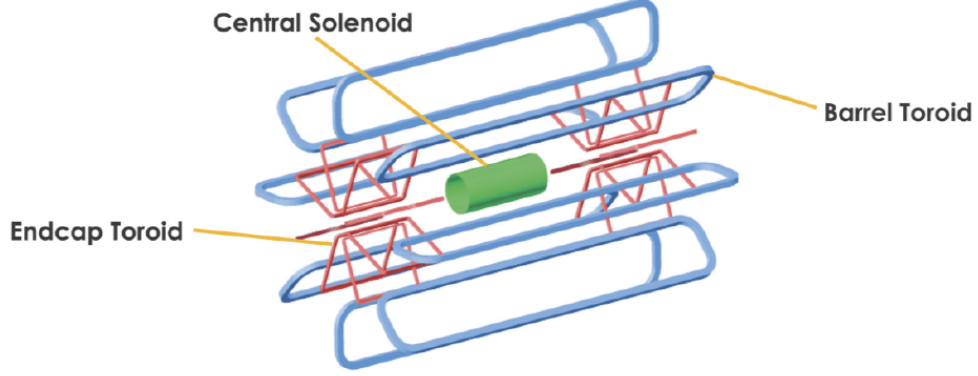


Figure 16: Layout of the ATLAS magnet system.

2.3.3 Inner detector

The inner detector (ID) [53, 54] is the closest ATLAS apparatus element to the interaction point. It is designed for the reconstruction of the path of charged particles produced in the pp collisions, as track, and of the primary vertices of the interactions and possible secondary vertices from the decay of long-lived particles.

The ID has a cylindrical shape around the interaction point with a radius of 1.1 [m] and a length of 6.2 [m]]. The trajectories of the charged particles are reconstructed through high-resolution position measurements known as hits. The entire ID is immersed in the solenoids magnetic field of 2 [T] provided by the barrel solenoid, which allows to measure the momentum and the charge of the particles from the curvature of the trajectory. Track and vertices are reconstructed using information from the ID. Track and vertex reconstruction are crucial for the identification of jets coming from b-quarks and hadronically decaying τ leptons, crucial in this thesis.

The inner detector provides accurate and efficient tracking for charged particles with $p_T > 0.5$ [GeV] within $|\eta| < 2.5$, with a transverse momentum resolution of:

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T \oplus 1\% \quad (62)$$

as shown in 1.

Three technologies are exploited to measure track hits: an innermost pixel detector composed of silicon pixels, an intermediate silicon strip detector (SCT) and an outermost transition radiation tracker (TRT). Figure 17 (a) shows a three-dimensional illustration of the ID layout, while Figure 17 (b) includes a more detailed layout.

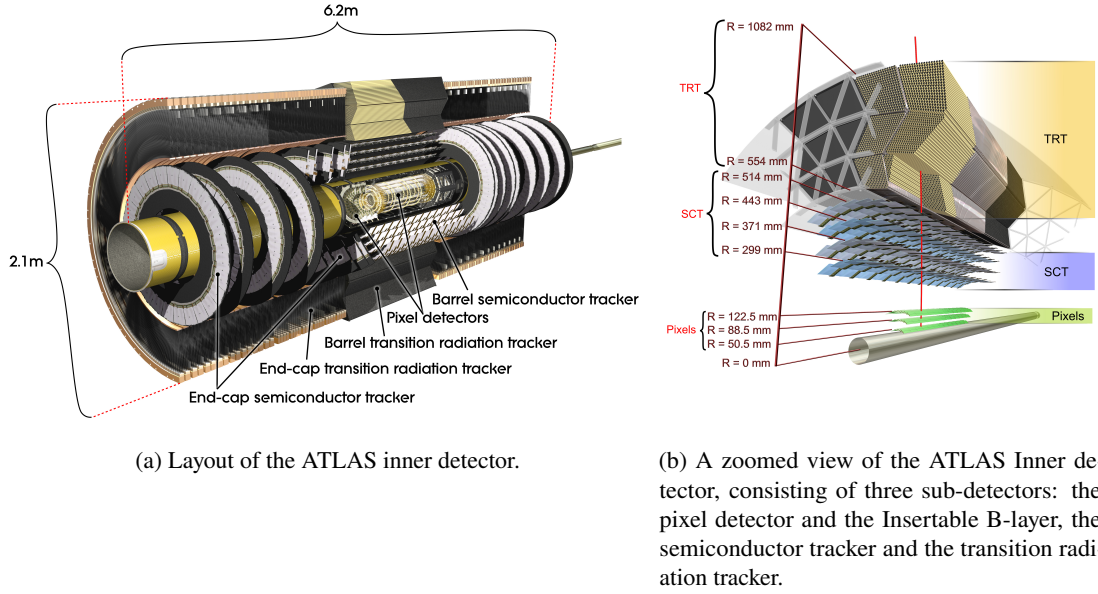


Figure 17: ATLAS inner detector [55].

2.3.4 Calorimeter system

The ATLAS calorimeter system [56] is placed outside the inner detector and its magnetic field. The purpose of the calorimeters is to measure the energy and position of particles. ATLAS uses sampling calorimeters to measure the energy and position of particles. ATLAS uses sampling calorimeters, where different materials, sandwiched together in layers, are used to initiate the shower development (absorption) and to measure the energy of its constituents. The position measurement is obtained by segmenting the calorimeter in the z and ϕ directions. ATLAS calorimeters cover the range $|\eta| < 4.9$ and they are divided into two distinct subsystems, the electromagnetic calorimeter, for measuring the energy of electrons and photons, and the hadronic, for measuring the energy of hadrons. Over the η region matched to the inner detector, the fine granularity of the electromagnetic calorimeter is ideally suited for precision measurements of electrons and photons energy. The less dense granularity of the rest of the calorimeter is sufficient to satisfy the physics requirements for jet energy measurements and missing transverse momentum measurements. Information from the calorimeter system are crucial for the reconstruction, identification and energy measurement of b-jets and hadronically decaying τ -leptons. The ATLAS calorimeter system is shown in Figure 18.

Electromagnetic calorimeter (EM)

The electromagnetic (EM) calorimeter is the innermost calorimeter and it used to measure the energy of electrons and photons. It is a sampling calorimeter where lead is used as absorber and liquid argon (Lar) is used as active material. It consists of accordion-shaped cells filled with liquid argon alternated with layers of lead.

The EM calorimeter consists of two half barrels (named EMB), extending to $|\eta| < 1.475$ (with a 4 [mm] gap at $z = 0$), and two wheels on each side in the end-caps (named EMEC), the first covering $1.375 < |\eta| < 2.5$ and second covering $2.5 < |\eta| < 2.5$. Additional material needed to instrument and cool the detector creates a "crack" region at $1.375 < |\eta| < 1.52$, where the energy resolution is significantly degraded.

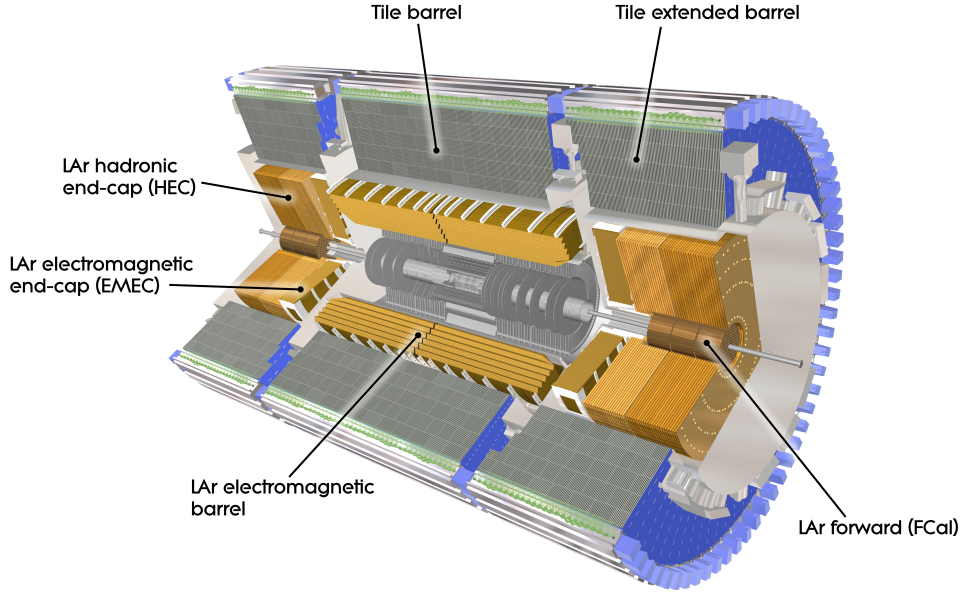


Figure 18: View of the ATLAS calorimeter system [57]

In the transverse direction, the calorimeter has three layers: a pre-sampler with very high granularity in η , which can reconstruct neutral pions decaying to two photons and particles whose shower already started in the inner detector. The pre-sampler is followed by longer towers with high granularity, which detect the bulk of the EM showers, and allow for measurements of the η and ϕ coordinates of the particles. The last layer detects showers generated from particles other than electrons or photons that start showering inside the EM calorimeter before leaving it.

Hadronic calorimeter (HCal)

The hadronic calorimeter (HCal) surrounds the EM one. It is for the purpose to measure the energy and the direction of hadrons produced by the hadronization of quarks and gluons. The ATLAS hadronic calorimeter is composed of three different parts:

- **Hadronic tile calorimeter:** It covers the region $|\eta| < 1.7$ and uses steel as absorber and plastic scintillator tiles as active material. It consists of a barrel covering $|\eta| < 0.8$ and two extended barrels covering $0.8 < |\eta| < 1.7$, and is located immediately behind the EM calorimeter. The scintillators are connected at each end to readout photomultiplier tubes by wavelength-shifting fibres. The fibres are grouped together to form readout cells, giving projective towers in η .
- **Hadronic LAr end-caps calorimeter (HEC):** The HEC consists of two Wheels per end-cap covering $1.5 < |\eta| < 3.2$ and located directly behind the EMEC. It uses copper as absorber and LAr as active material.
- **Forward calorimeter (FCal):** The FCal covers $3.1 < |\eta| < 4.9$. Due to the high particle fluxes and energies in the forward region, the calorimeter must contain relatively long showers in the small volume allowed by design constraints, and thus must be very dense. It is divided into three compartments. The first is designed for electromagnetic measurements, and uses copper as a passive

material with liquid argon as active material. The other two compartments are designed for hadronic measurements, and use a tungsten as a passive material, chosen for its high density to provide containment and minimise the lateral spread of hadronic showers.

2.3.5 Muon spectrometer

The muon spectrometer (MS) [58] is the outermost and largest detector of ATLAS. It fully covers the calorimeter system and occupies a large part of the ATLAS cavern. It is designed to identify muons and measure their momentum in the p_T range from about 10 [GeV] up to the order of 1 [TeV]. It adopts different detector technologies for accurate momentum and direction measurements of muons and efficient triggering.

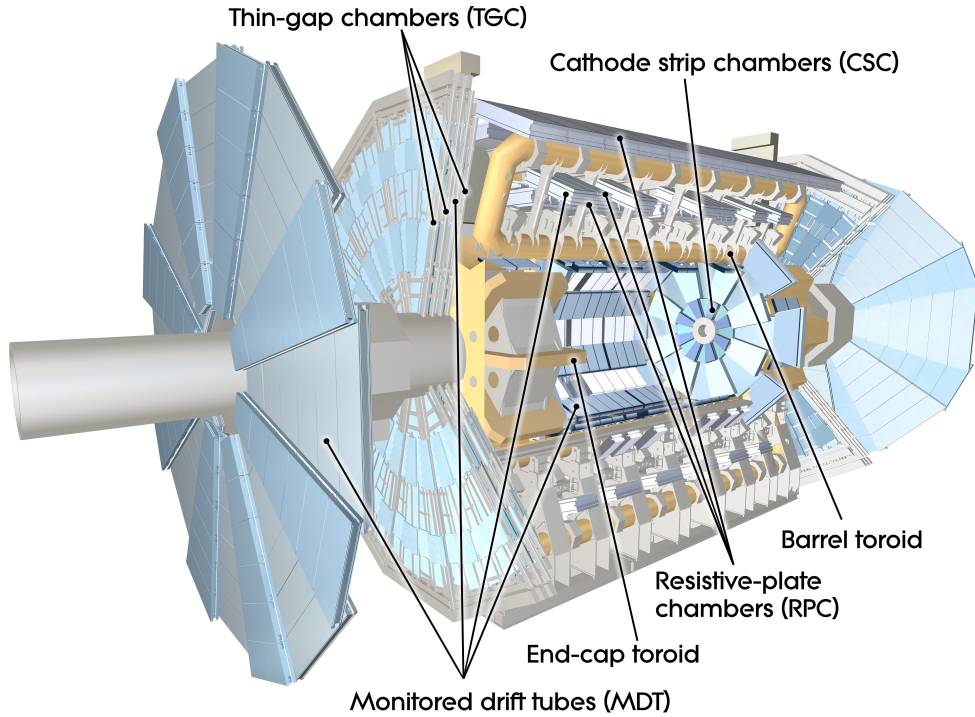


Figure 19: View of the ATLAS muon spectrometer [58]

The complete layout of the muon spectrometer is shown in Figure 19. It covers the range $|\eta| < 2.7$ and, as shown in Table 1, its design benchmark is a 10% transverse momentum resolution for 1 [TeV] muon tracks. The four subsystems composing the muon spectrometer rely on four different gas detector technologies. Two of them, the resistive plate chamber (RPC) in the barrel region and the thin gap chambers (TGC) in the end-cap region, provide trigger signals, while the other two, the monitored drift tubes (MDT) and the cathode strip chambers (CSC) provide the momentum measurement. The MDT chambers provide high precision measurements in the bending direction over most of the detector acceptance while the CSC are used in the forward region where the particle flux is too high for the MDT chamber. The muon chambers are arranged in the barrel ($|\eta| < 1.05$) in three cylindrical layers around the beam axis, while in the end-cap regions ($1.05 < \eta < 2.7$) they are placed in three wheels.

3 Trigger system

The LHC is designed to observe up to 1.7 billion proton-proton collisions per second (and a bunch crossings every 25 [ns]), with a combined data volume of more than 60 million megabytes per second. However, only some of these events will contain interesting characteristics that might lead to new discoveries. The Trigger and Data Acquisition system [59, 60] ensure optimal data-taking condition and select the most interesting collision events.

As shown in the Figure 20, it analyses online events at two successive levels of increasing complexity that allow it to reduce the event rate through a hardware Level-1 (L1) and a software-based high-level-trigger (HLT). The L1 trigger determines the regions of interest (RoIs) in the calorimeters and in the muon spectrometer using fast dedicated hardware, and reducing the rate from 40 [MHz] to 100[kHz] with about 2.5 [μ s] of total latency. The HLT consists of fast algorithms accessing data from a RoI or using the full event information. It has access to the high-granularity and full-precision information from the calorimeters, the muon spectrometer and the inner detector, and it is software-based. The algorithms used in the HLT are similar to the physics objects reconstruction and identification algorithms, but they are less precise as they must be faster. They are used to select events containing physics objects which are electrons, muon, photon, jets or τ -lepton candidates that are events of interest for ATLAS physics program. This trigger level reduces the rate of events by two orders of magnitude, reaching an average of 1 [kHz] with a latency of 0.2 [μ s].

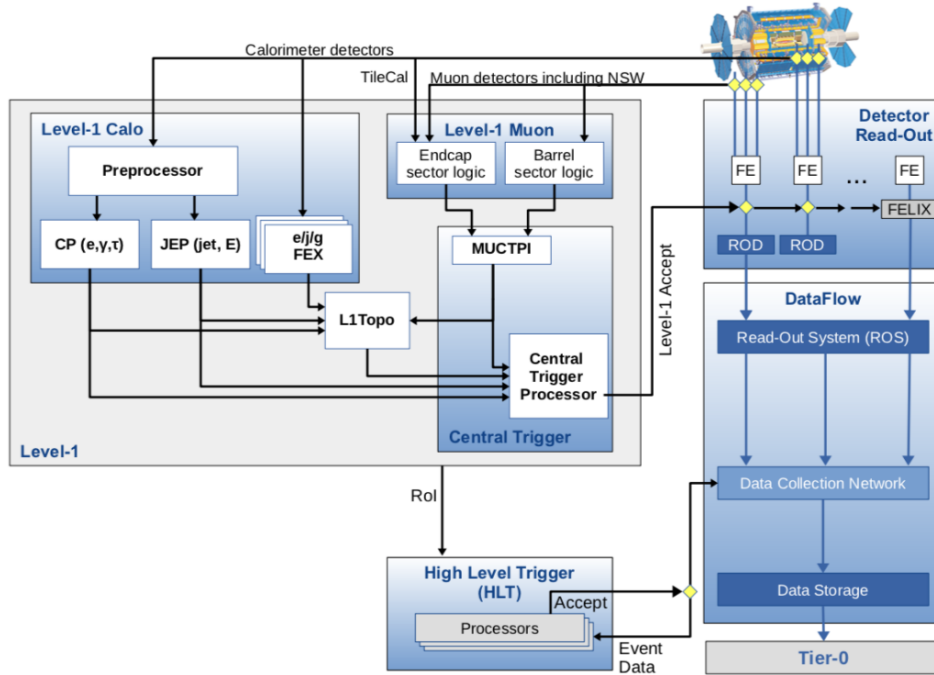


Figure 20: An overview of the ATLAS trigger and DAQ system [59]

The Data Acquisition (DAQ) system monitors the recording of the data on storage disk. If the L1 system trigger an event, the DAQ moves the event data from the detector electronics to detector-specific Read-Out Drivers. If the event passes also the HLT, the event data data are merged together and recorded to disk.

The trigger system is the main theme of this thesis, as discuss in the following chapters on the context of

the Qualification Task done for the ATLAS experiment. Specifically, some implementations were done for the monitoring tau trigger master(legacy) code, at the end of the Run 2 analysis and part of the data-taking period for Run 3.

3.1 Trigger menu design

As discussed in the previous section 3 and shown in the Figure 20, the 'Dataflow' system consists in the collection various events of interest for the permanent storage. The Qualification Task was development in various implementations, improvements and monitored analysis of this stage. Therefore, it would be necessary to introduce the trigger menu system and its operations.

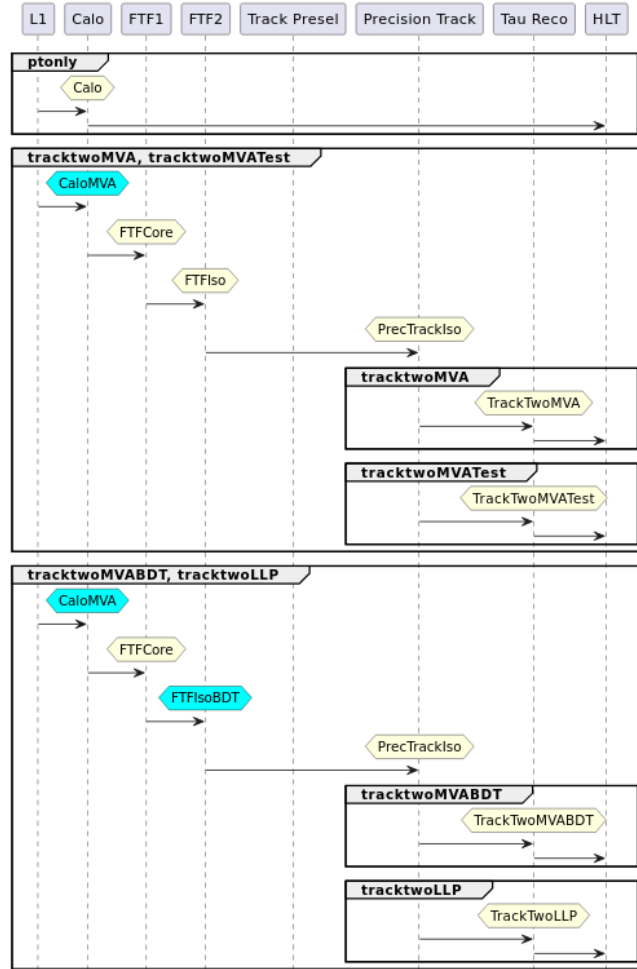


Figure 21: Trigger menu sequence.

Event selections in the HLT are referred as triggers, and the collection of all L1 and HLT triggers and their prescales is called the trigger menu (see table 4 for τ 's). Triggers are comprised of steps, where a step is a sequence of algorithms. A typical step will execute multiple feature-extraction algorithms requesting event-data fragments from within a rectangular (in $\eta \times \phi$) Region of Interest (RoI) defined by the L1 output, and run reconstruction algorithms over this sub-set of the event data. Each step terminates on a hypothesis

algorithm, which uses the reconstructed features to form a boolean decision whether the trigger condition is satisfied. Triggers can also comprise a single hypothesis algorithm that makes no additional selection on an event after the L1 trigger; triggers with this selection are referred to as pass-through. The output of single algorithms and entire is cached, as is the partial-event data requested by feature extraction algorithms, and any subsequent request for the same algorithm/step (within the same RoI) or data fragment(s) within the event processing returns the local cached version. Each L1 and HLT trigger has an associated prescale p_{L1} and p_{HLT} , respectively, which take values ≥ 1 . Only $1/p_{L1}$ events passing by a L1 trigger accepted for HLT processing and only $1/p_{HLT}$ events passing the L1 selection required by an HLT trigger are processed at HLT. Trigger with both $p_{L1} = 1$ and $p_{HLT} = 1$ are referred to as unprescaled [61].

The trigger menu strategy is based on the following building blocks:

- Primary triggers, which are used for efficiency and performance measurements, and typically run unprescaled.
- Support triggers, which are used for efficiency and performance measurements, background estimates or monitoring, and typically run at a small rate (of order of 0.5 [Hz] each, with prescales). about 15% of the HLT bandwidth is dedicated to support triggers.
- Alternative triggers, which run alternative online reconstruction algorithms complementary to primary and/or support triggers, and are used, for example, as part of the commissioning of future primary triggers.
- Calibration triggers, which are used for detector calibration, and often run at high rates that are compensated by storing only the necessary detector information for each event, thus reducing the event size and overall bandwidth.

The convention in the name to each chains follow the next structure,

HLT_(pt reco cut)_(selection)_(preselection)_(L1seed)

therefore, as a summary in the tau trigger code, can be seen the next descriptions:

- The tau pt cut description, like '*tau25*' means a pt threshold of 25[GeV] reconstructed.
- The selection, for ID on the TrigTauJet is described by, nTracks and identification cuts applied, whose possible values are :
 - idperf, no nTrack nor ID cut.
 - perf, nTrack cut but no ID cut.
 - mediumRNN, nTrack cut and RNN ID cut
- The preselection deals of tracking and track counting scheme. whose possible values are:
 - tracktwo, 2-step fast-tracking we count tracks from fast tracking.
 - tracktwoMVA, same as tracktwo, with a MVA pt calibration.
 - tracktwoRNN, same as first, with a RNN pt calibration.
 - tracktwoMVABDT, same as tracktwo, with MVABDT pt calibration.

The complete trigger menu has to respect all technical limitation at L1 and the HLT, which makes the alignment of the physics goals of the menu with the available resources in terms of bandwidth and CPU in the HLT farm a challenging task. Recorded events are gathered in data streams, depending on their primary use case and their specific offline reconstruction needs. The performance of each stream to date can be seen in Ref. [62].

3.2 Athena Multi-Threading architecture

In Section 3.1 was discussed the different algorithms that the chains passes through the Tau Trigger Code. The main framework uses in ATLAS is Athena that usually undergoes updates and improvements in focus to a better development of the software. In this sense, in the Run 2 analysis period, the tau trigger code was rewritten due to a completely change of its philosophy. In fact, this code restructuring only affects the master branch and it passed from 'Multi-processes' (MP) to a 'Multi-threading' software framework (AthenaMT)[63]. Due to increase of luminosity that reached up to three times the original design value at 2021 data-taking and also a expected luminosity increase to up to 7.5 the design value, in 2026 following LHC and ATLAS upgrades. The ATLAS trigger architecture will result in an increase in the high level trigger input rate by a factor of 4 to 10 compared to the current maximum rate of 100 [kHz]. The MP software framework manages a number of processes that process events independently, executing potential to significantly reduce the memory footprint on future many-core device. Instead, the AthenaMT will provide a fully multi-threaded environment that will enable concurrent execution of algorithms also within an event. This has the potential to significantly reduce the memory footprint on future many-core devices. An additional benefit of the High Level Trigger implementation within the AthenaMT is that it facilitates the integration of offline code into the High Level Trigger. The trigger must retain high rejection in the face of increasing numbers of pile-up collisions. This will be achieved by greater use of offline algorithms that are designed to maximize the discrimination of signal from background. Therefore a unification of the High Level Trigger and offline reconstruction software environment is required. This has been achieved while at the same time retaining important High Level Trigger-specific optimisations that minimize the computation performed to reach a trigger decision. Such optimizations include early event rejection and reconstruction within restricted geometrical regions.

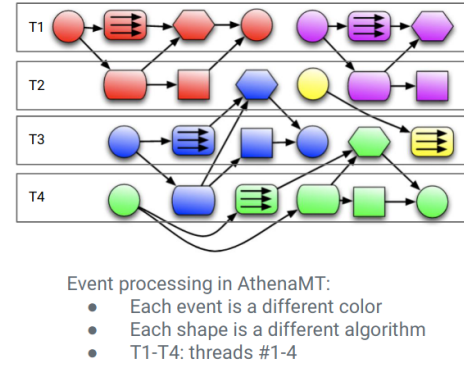


Figure 22: Algorithm athenaMT (philosophy).

4 Legacy implementation & analysis

The first implementation is completely related with the Section 3. A new chains implementation was development in legacy code using MP framework software. The main goal was the analysis of the kinematic behavior of the new chains in reference to a current one. The new chains presented under study had a new track classifier algorithm called 'tracktwoMVABDT' and 'tracktwoRNN'. Also, after the implementation a fixed in the denominator used in the calculation of its efficiencies was performed taking in count the working-point of each chain under analysis.

The correct efficiency curve distribution was performed in base to fix the classifier between two basic categories that the codes used to identify how to apply the denominator. The two categories depends if the track algorithm run by Boosted Decision Trees (BDT) or by Red Neuronal Network (RNN), recently implemented. Therefore, all this developments were useful to get the correct production of the efficiencies, as it shown from Figure 23 to Figure 25 for L1 and from Figure 26 to Figure 28.

The efficiencies histograms are built with respect the tau reconstructed from the L1 stage or HLT stage and the equation is as follow:

$$Efficiency = \frac{N^{\circ} \text{ events pass criteria}}{Total \ N^{\circ} \text{ events}} \quad (63)$$

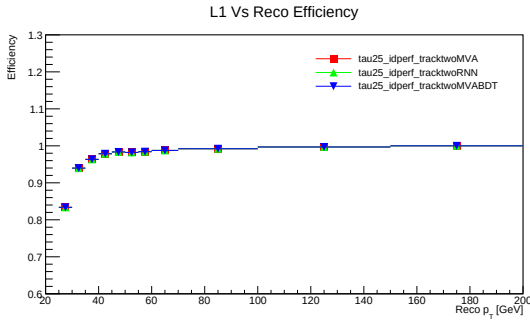


Figure 23: L1 Pt vs Efficiency. *idperf* chains

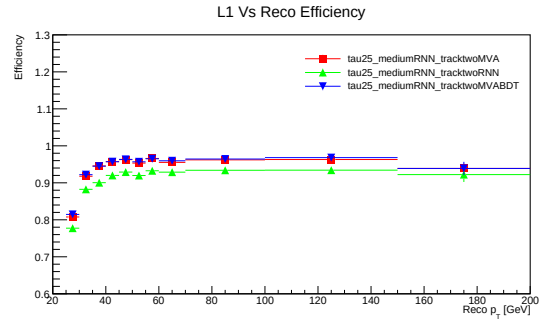


Figure 24: L1 Pt vs Efficiency. *mediumRNN* chains

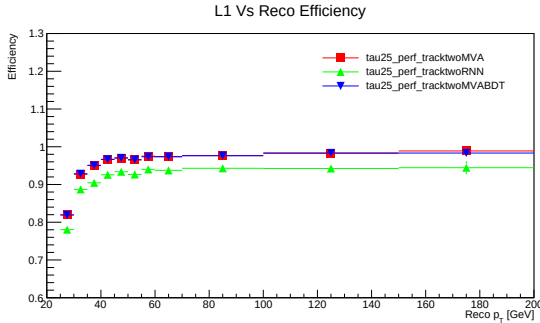


Figure 25: L1 Pt vs Efficiency. *mediumRNN* chains

Due in the up-left histogram the category implies that there is not cut ID nor Track cut, So each chains should has the same efficiency curve, as we can see in figure 23. Form the others categories the curve must not be the same, like 'perf', there is ID and track cut. in the histograms with almost one cut the tracktwoMVABDT presents the best efficiency, follow of TracktwoMVA, where tracktwoRNN has the worst efficiency.

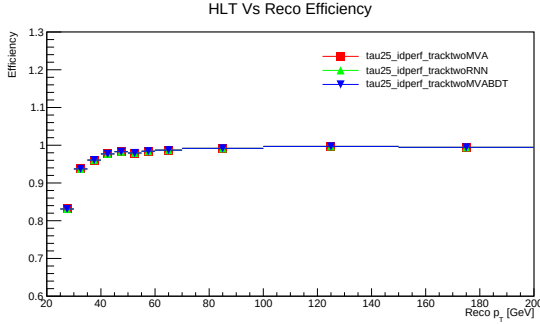


Figure 26: HLT Pt vs Efficiency. *idperf* chains.

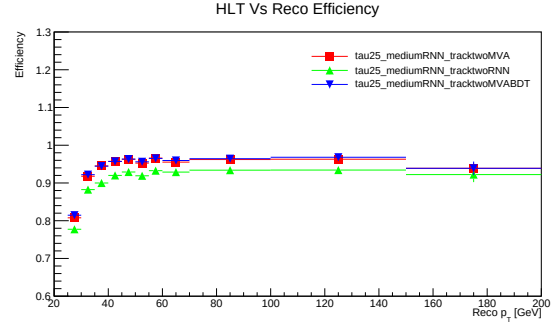


Figure 27: HLT Pt vs Efficiency. *mediumRNN* chains

With the τ events pass L1, the offline reconstruction follow, and the matching of the curves are similar to the previous scenario. The *idperf* that lacks cuts to each chain looked here, will present only one shape of curve to each triggers. Different behavior are in the other two categories.

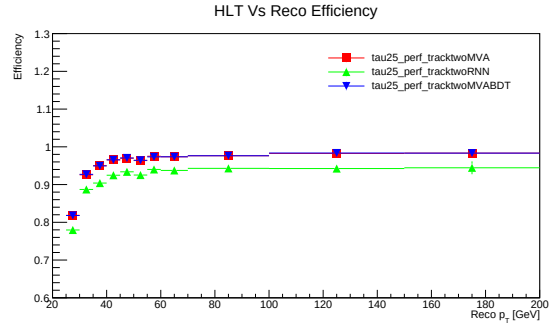


Figure 28: HLT Pt vs Efficiency. *perf* chain.

4.1 Results

The results of the histograms are as expected, more of them are in the Auxiliary material Section B. The correct distribution of the efficiency respect its current working-point illustrates which one presents the better efficiency with the tracktwoMVA as reference. The last implementations were fix the matching function between Offline events and online events and some improvement in the skeleton of the folder for chain with L1 seeds, part the output monitoring of the legacy code, as shown in figure 29.

5 Truth quantities in Trigger Tau monitoring

As far as further developments are concerned, they are developed in the master branch of the Trigger tau monitoring code, this means after the migration to the multi-threading software framework detailed in the Section 3.2.

The *truth quantities* come from MC samples, which the code uses these simulated events to contrast with real data, in these case for getting tau candidates. The truth events has the missing energy added, therefore

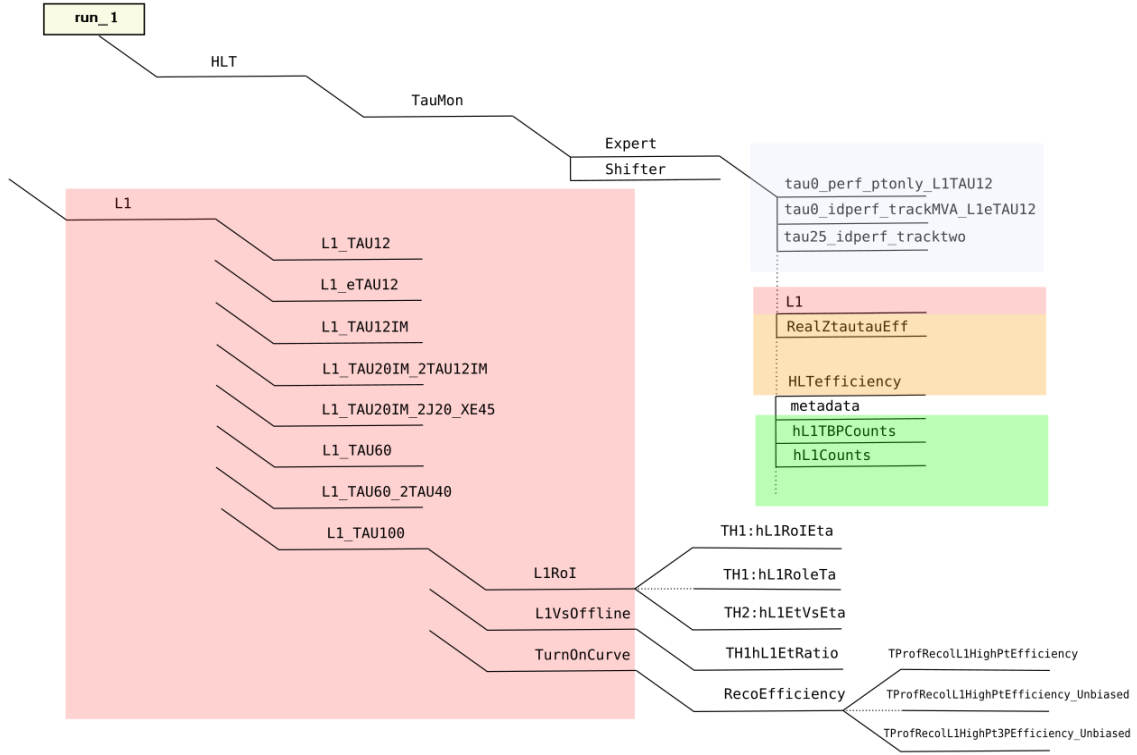


Figure 29: New folder (Red) in menu monitoring at release 21.3. To avoid the duplication folder was created in Expert level along with chains (Gray), monitoring folders (orange) and general histograms (Green).

when the truth quantities is removes that missing energy, it called *visible quantities*. Taking this into account, from the context of the implementation, was performed a suitable analysis of the kinematic visible variables for all trigger chains in the code. It observed an expected behavior of the chains stored in two important monitoring folders, 'EFVsTruth' and 'TruthEfficiency'. In the first folder, it was adding p_t , η , ϕ , μ , etc. but also, profile histograms, that shows the bias of these kinematic variables from 0, with the ratio calculation,

$$ratio = \frac{(reco\ p_t - truth\ visible\ p_t)}{truth\ visible\ p_t} \quad (64)$$

where $reco\ p_t$ is the transverse moment of the tau reconstructed, and $truth\ visible\ p_t$ is the visible tau. The second folder implemented is related to the efficiency calculation. The reason for this is because if there is a problem that affects both the trigger and reco selection in the same way, then we would not see this in the efficiency relative to reconstructed taus. The calculus of the efficiency in this case is determined by,

$$eff_{truth, HLT} = \frac{HLT\ matched\ truth\ \tau's}{total\ truth\ \tau's} \quad (65)$$

and follow these previous requirements encoded in the algorithm:

- Truth Tau exits.
- Truth Tau passes trigger requirements.
- The $\Delta R < 0.2$ between visible taus particles and τ 's in High level trigger stage.

5.1 Results

All the histograms shown in this section, are plotted with ttbar sample according table 2. The Figure 30 and 31 illustrates different curves with the same cut threshold, track classifier and seed, but different working points. The curve with more events cover all range (x-axis) is the 'idperf' type, which the other ones gets worse number of the events. all is in agreement what it expected, because are in relation with cuts applied to each chains.

On the other hand, the profile histograms, in the Figure 32, Figure 33 and 34, presents that the largest discrepancy between the reconstructed taus particle and the visible taus particle is on the part of the idperf chain type. This means, the mediumRNN gets the best agreement between the taus particles that come from the reconstruction and the taus particles from the simulated taus, considering all the kinematic variables showed in the histograms.

Finally, in the same sense discussed in the first paragraph about the number of filters applied in each chain, the better efficiency showed in Figure 35 is the chain with 'idperf' description. Also, can be seen how each efficiency curve activation is depend of the p_t threshold associated to the chain, shown in figure 36, as expected.

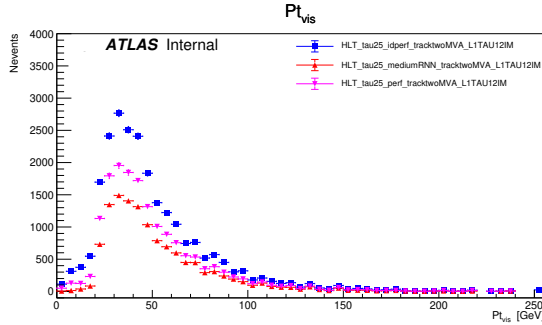


Figure 30: Pt_{vis} v/s N° Events.

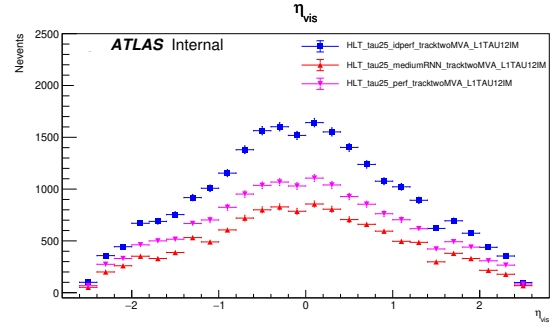


Figure 31: η_{vis} v/s N° events.

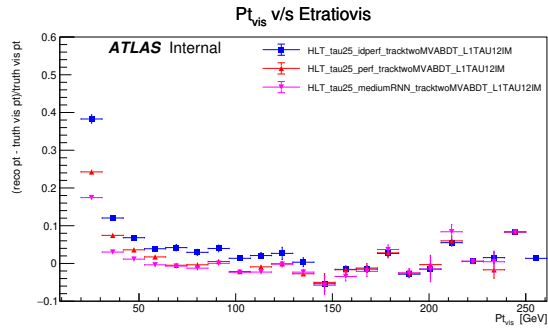


Figure 32: Pt_{vis} v/s Etratiovis.

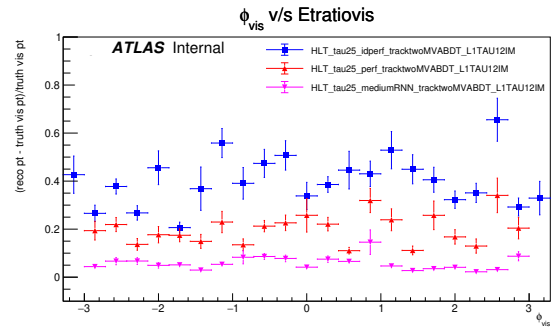


Figure 33: ϕ_{vis} v/s Etratiovis.

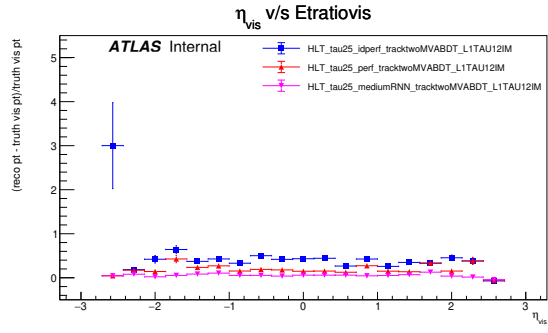


Figure 34: η_{vis} v/s Etratiovis.

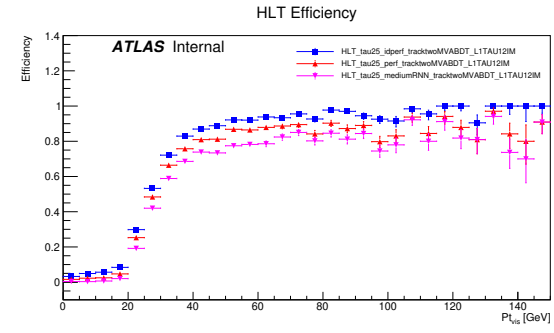


Figure 35: Pt_{vis} v/s Efficiency.

HLT Efficiency t $\bar{t}$ sample

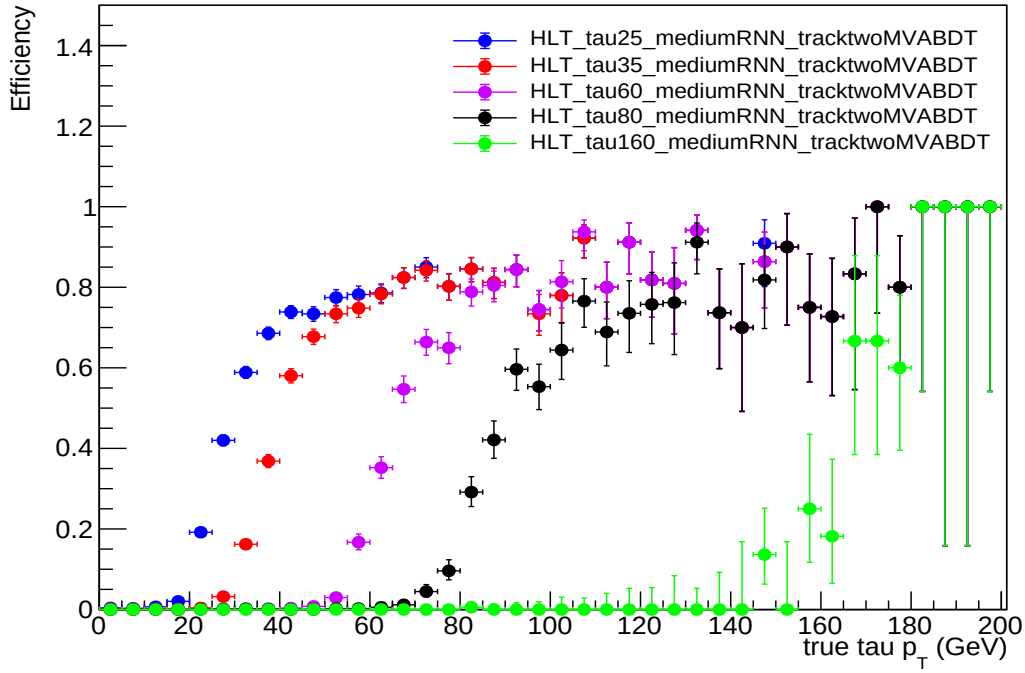


Figure 36: true tau p_t v/s Etratio.

6 Di-tau systems in trigger tau monitoring.

DiTau chains are implemented. The studies of this chains are frequently used for several studies of the Higgs Boson. Each decay, with a double tau production try with this information and with its futures analysis. The addition of variables contemplates momentum Pt, pseudo-rapidity η , polar angle ϕ , Mass M and the difference of each (leading and subleading) τ particles named $|dPt|$.

The number of the events in all range of values for each kinematic variable depends at first of the threshold of the chains as we expected. In general, all the histograms present the same result in different pt calibration. The categories 'tracktwoMVA' and 'tracktwoMVABDT' for 25 [GeV] threshold has the basically the same performance.

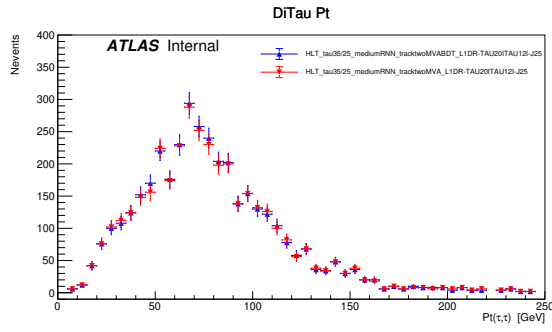


Figure 37: Pt v/s Nevents.

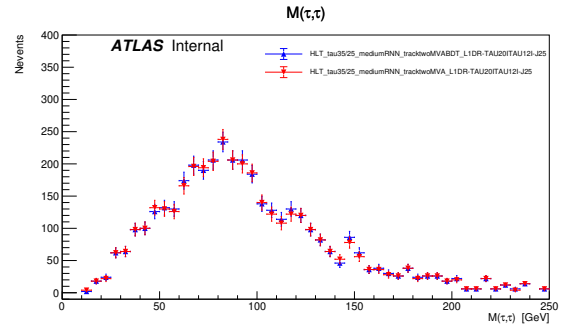


Figure 38: M v/s Nevents.

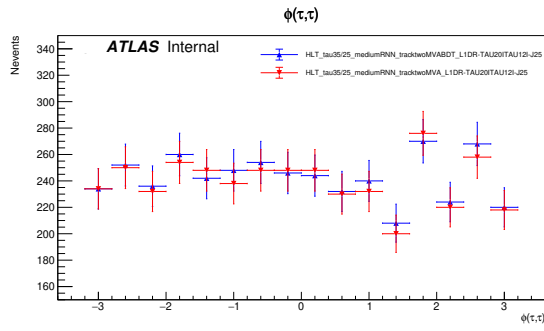


Figure 39: $|dPt|$ vs Nevents.

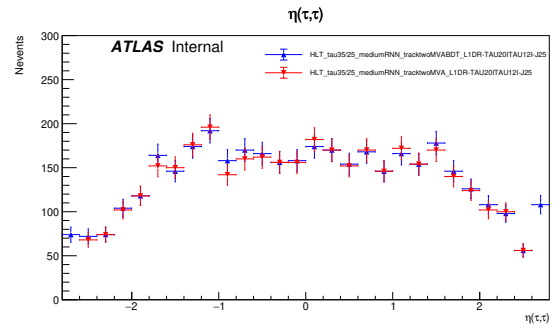


Figure 40: η v/s Nevents.

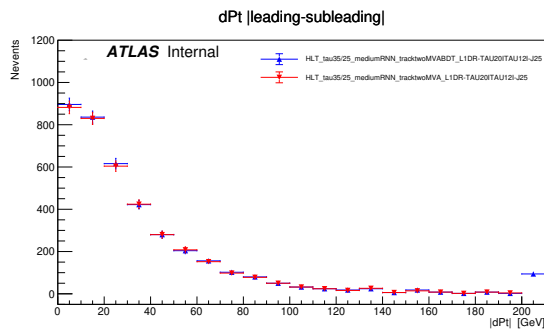


Figure 41: ϕ v/s Nevents.

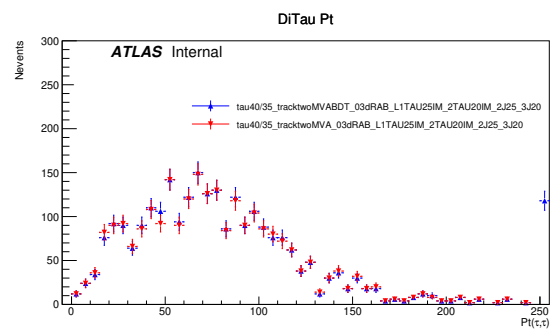


Figure 42: Pt v/s Nevents.

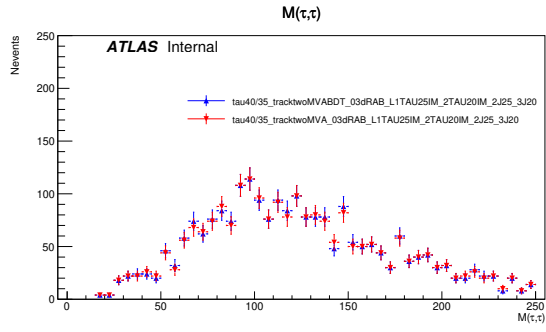


Figure 43: M v/s Nevents.

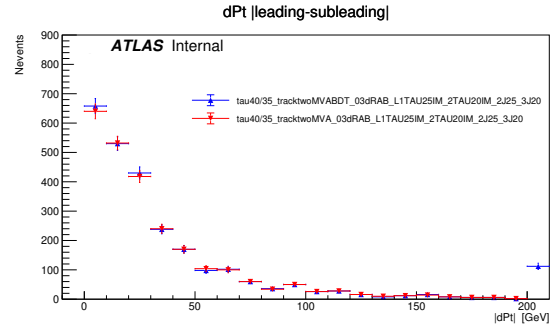


Figure 44: $|dPt|$ v/s Nevents.

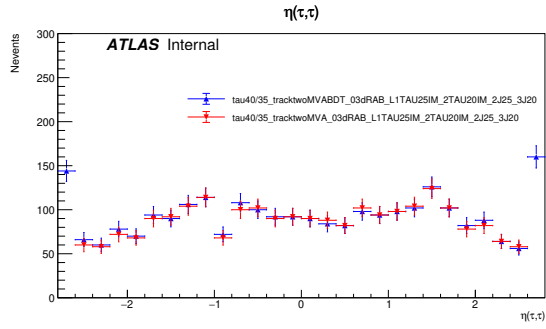


Figure 45: η v/s Nevents.

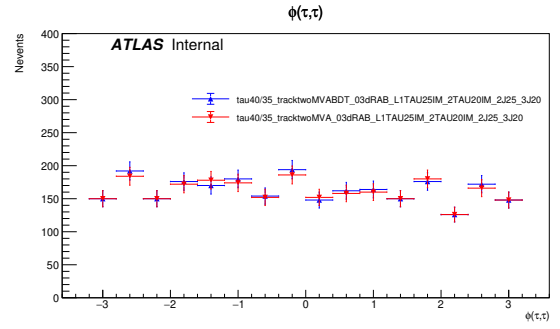


Figure 46: ϕ v/s Nevents.

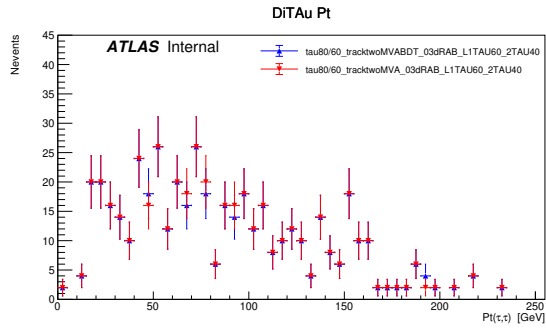


Figure 47: Pt v/s Nevents.

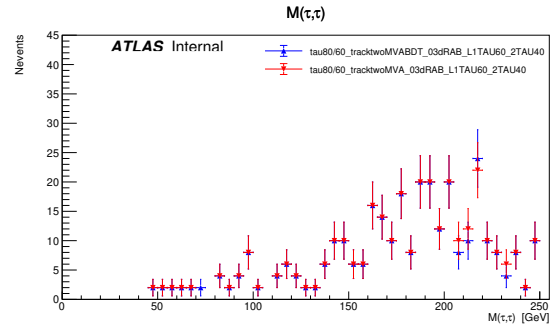


Figure 48: M v/s Nevents.

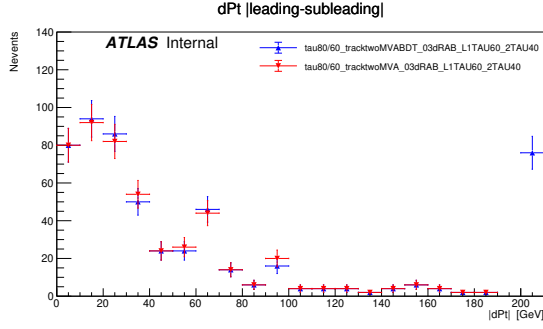


Figure 49: $|dPt|$ v/s Nevents.

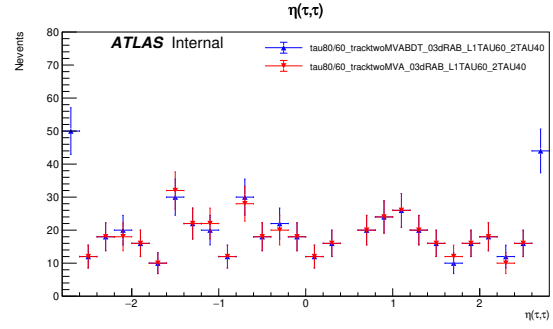


Figure 50: η v/s Nevents.

7 χ^2 test between different reprocessing

To date, the Run 3 data-taking is in course. Generally, for all the data information available ordered in runs processing, it is chosen reference when all analysis is in agreement with the behavior of the all histogram. with the increase of luminosity and the updates of the software, it is necessary to re-elect a new reference. In this sense, it was performed a study with the objective of promoting a new reference taking into account the relationship that exists with the current reference, doing an Xi-square test. In this case, to be more precise, the current reference in 'Physics main stream' to date (run 431885).

7.1 χ^2 - test for comparison of unweighted histograms

A frequently used technique in data analysis is the comparison of histograms. This section develops the χ^2 test of homogeneity is used for comparing usual unweighted histograms [64].

Comparison of two histograms expected hypotheses that two histograms represent identical distribution. To make a decision p-value should be calculated. The hypotheses of identify is rejected if the p-value is lower then some significance level. Traditionally significance levels $\alpha = 0.05$ is used.

Methods of comparison

Let us consider two histograms with the same binning and the number of bins equal to r . Let us denote the number of events in the i -th bin in the first histogram as n_i and as m_i in the second one. The total number of events in the first and second histogram is equal to:

$$N = \sum_{i=1}^r n_i \quad M = \sum_{i=1}^r m_i \quad (66)$$

The hypothesis if identify (homogeneity) [65] is that the two histograms represent random values with identical distribution. It is equivalent that there exist r constants $p_1, \dots, p_r$, such that

$$\sum_{i=1}^r p_i = 1 \quad (67)$$

and the probability of belonging to the i th bin for some measured value in both experiment is equal to p_i . The number of events in the i th bin is a random variable with a distribution approximated by a Poisson probability distribution

$$\frac{e^{-Np_i} (Np_i)^{n_i}}{n_i!} \quad (68)$$

for the first histogram and with distribution

$$\frac{e^{-Mp_i} (Mp_i)^{m_i}}{m_i!} \quad (69)$$

for the second histogram. If the hypothesis of homogeneity is valid then the maximum likelihood estimator of p_i , $i = 1, \dots, r$ is

$$\hat{p}_i = \frac{n_i + m_i}{N + M} \quad (70)$$

and then

$$\chi^2 = \sum_{i=1}^r \frac{(n_i - N\hat{p}_i)^2}{N\hat{p}_i} + \sum_{i=1}^r \frac{(m_i - M\hat{p}_i)^2}{M\hat{p}_i} = \frac{1}{NM} \sum_{i=1}^r \frac{Mn_i - Nm_i}{n_i + m_i} \quad (71)$$

has approximately a χ^2_{r-1} distribution [65].

7.1.1 Results

With the last section method as a reference, it applies this test for the same histograms in the 'HLT efficiency' folder to each chain for the all 211 run in the physic main stream for the tau trigger data. the 'run' with the best result is:

Physics_Main_Run431885+Physics
Run439927/HLT_Efficiency
HLT_tau25_idperf_tracktwoMVA.L1TAU12IM
1P-3P

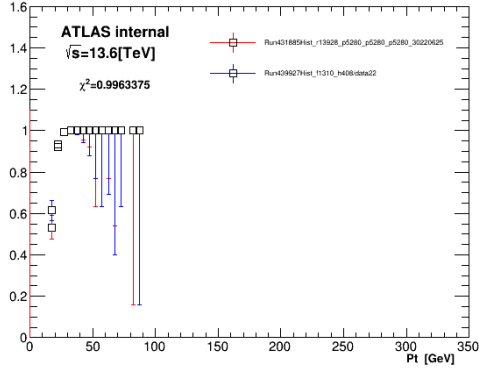


Figure 51: Pt v/s Efficiency.
1P

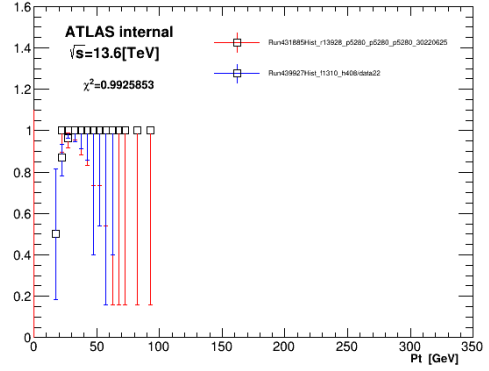


Figure 52: Pt v/s Nevents.
3P

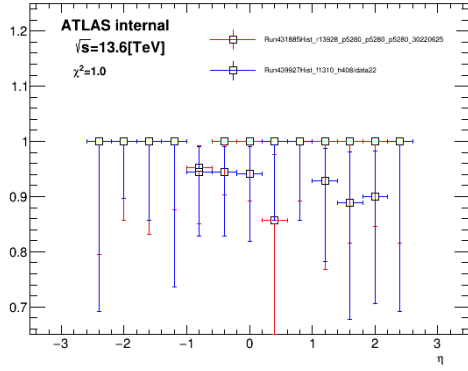


Figure 53: η v/s Efficiency.
3P

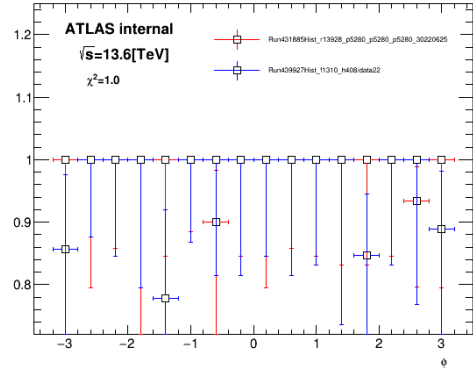


Figure 54: ϕ v/s Efficiency.
3P

Physics_Main_Run431885+Physics
Run439927/HLT_Efficiency
HLT_tau25_mediumRNN_tracktwoMVA_L1TAU12IM
1P-3P

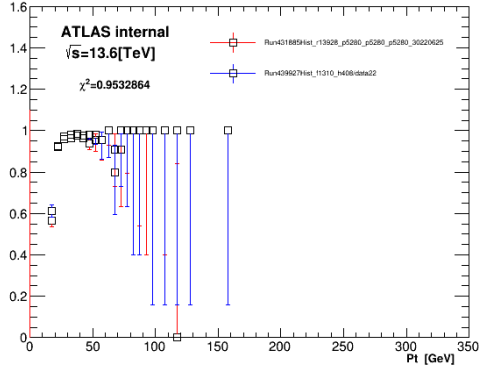


Figure 55: Pt v/s Efficiency.
1P

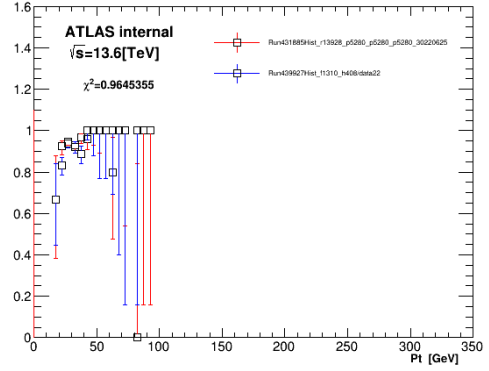


Figure 56: Pt v/s Nevents.
3P

Physics_Main_Run431885+Physics
Run439927/HLT_Efficiency
HLT_tau35_idperf_tracktwoMVA_L1TAU12IM
1P-3P

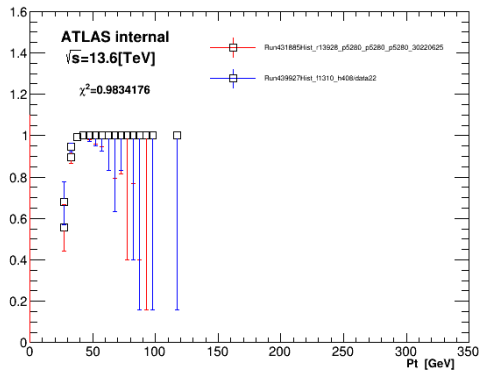


Figure 57: Pt v/s Efficiency.
1P

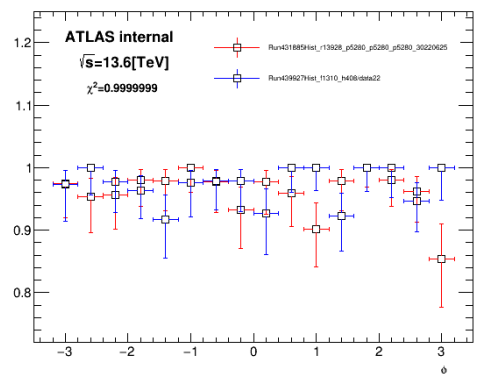


Figure 58: Pt v/s Nevents.
1P

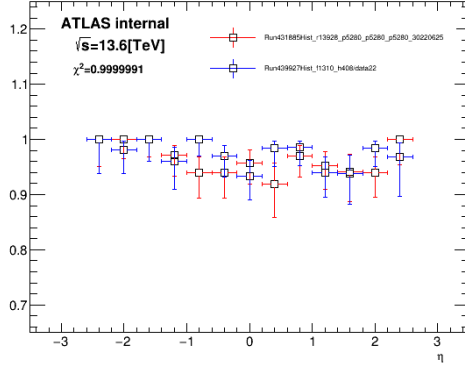


Figure 59: Pt v/s Efficiency.
1P

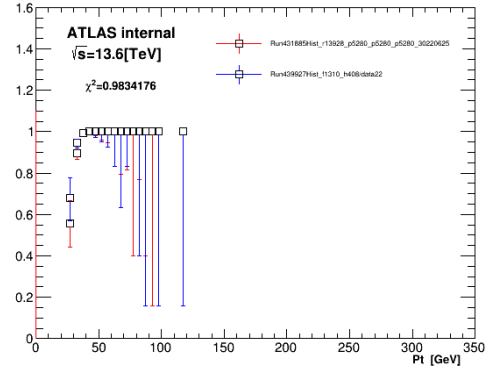


Figure 60: Pt v/s Nevents.
3P

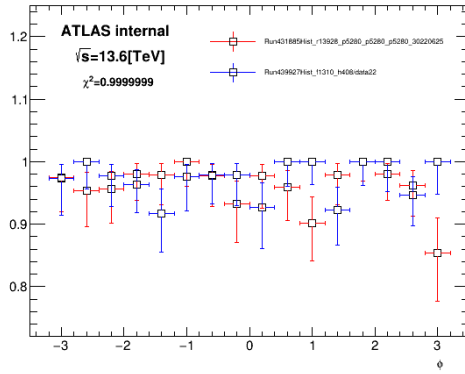


Figure 61: ϕ v/s Efficiency.
3P

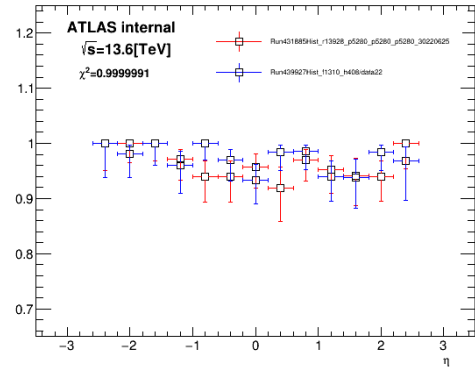


Figure 62: η v/s Nevents.
3P

Physics_Main_Run431885+Physics
Run439927/HLT_Efficiency
HLT_tau60_mediumRNN_tracktwoMVA_L1TAU100
1P-3P

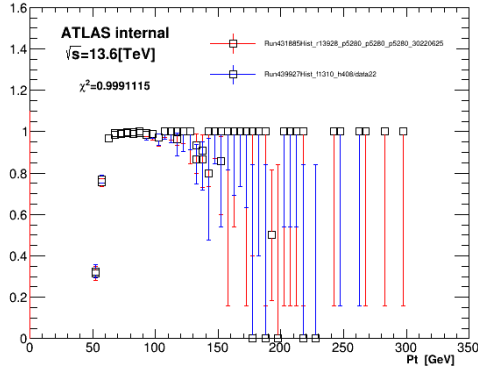


Figure 63: ϕ v/s Efficiency.
1P

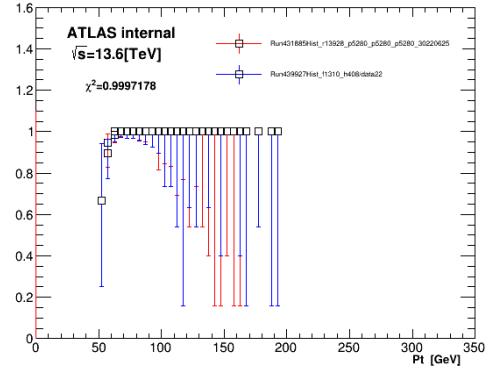


Figure 64: Pt v/s Nevents.
3P

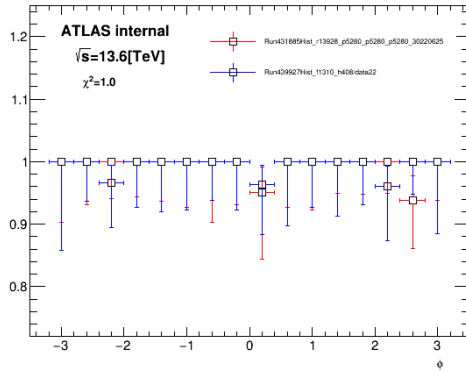


Figure 65: ϕ v/s Efficiency.
3P

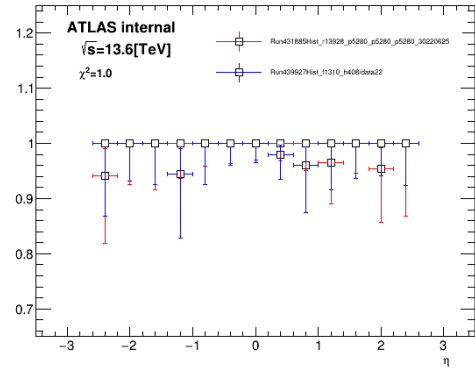


Figure 66: η v/s Nevents.
3P

From figure 51 to 66 shows the results of better processing in comparison with the reference. For 'Tau25' 'Tau35' and 'Tau60' chains. The histograms are calculated taking into account unweighted curves and they presents the score more closest to one between other 'Runs'. Then, It is proposed as a new reference among the entire database studied, taking into account a high 'tag', best response of the Xi squared test rounding the test value to 7 significant numbers.

8 Samples improvement for non-resonant $b\bar{b}\tau_{lep}\tau_{had}$ channel

In this chapter, it is the last work done for the thesis. It was development in the context of the later studies performance in ATLAS experiment. Specifically, the studies related with the Higgs boson discussed in Section 1.4. First, it will show some summary of the samples used in the studies of the pair decays of the Higgs boson, then, will describe the improvement perform to this channel.

8.1 Brief introduction to Higgs pair decay

To connect with the first sections of this document, it reminds that the SM predicts non-resonant HH production, with approximately 90% of the total cross-section being due to the gluon-gluon fusion (ggF) process. The leading-order (LO) contribution to ggF HH production are the 'triangle diagram', which includes a Higgs boson self-coupling vertex, and the heavy-quark 'box diagram', which has two fermion-fermion-Higgs vertices, see Figure 6. These diagrams interfere destructively, leading to a small SM ggF non-resonant HH cross-section, which is predicted to be $31.1^{+2.1}_{-7.2}$ [fb] at next-to-next-to-leading (NNLO) order in α_s , including an approximation of finite top-quark-mass effect, for $m_H = 125$ [GeV] and $\sqrt{s} = 13$ [TeV] [3, 66–72]. due to that small cross sections together with VBF, an observation of SM non-resonant HH production is not expected with the currently available LHC data set, although significant non-resonant and resonant enhancements to the HH cross-section are predicted in many beyond-the-SM (BSM) theories, See Appendix A.

Non-resonant HH production is a sensitive probe of the Higgs boson trilinear self-coupling and the shape of the Higgs field potential, which have important implications for the stability of the electroweak vacuum [73, 74] and for baryogenesis [75] and inflation [76, 77].

Previous searches for non-resonant HH production were performed by ATLAS and CMS in various channels. In the $b\bar{b}\tau^+\tau^-$ decay channel, ATLAS and CMS set observed (expected) upper limits on the non-resonant HH production cross section at 12.7 (14.8) [78] and 30 (25) [79] times the SM expectation using 36.1 [fb⁻¹] and 35.9 [fb⁻¹] of 13 [TeV] pp collision data, respectively. Using these data sets, ATLAS and CMS each combined their results from several search channels, improving these observed (expected) limits to 6.9 (10) [80] and 22.2 (12.8) [81] times the SM expectation, respectively. ATLAS and CMS have performed combinations of HH searches using their full Run-2 datasets, which set observed (expected) upper limits on the SM non-resonant HH cross-section at 2.4 (2.9) and 3.4 (2.5) times the SM expectation, respectively [82, 83]

The size fraction of all possible SM decays that result in this final states, $\mathcal{B}(HH \rightarrow b\bar{b}\tau^+\tau^-) = 7.3\%$ [84, 85], and relatively low backgrounds make this one of the most sensitive HH search signatures.

8.2 Data and simulation samples

the data used, were collected at a centre of mass energy of 13 [TeV] between 2015 and 2018, using triggers to select events with at least one lepton (where a lepton is defined as an electron or a muon). The recorded events contain an average of 34 simultaneous inelastic pp collisions per bunch-crossing and a integrated luminosity 139.0 ± 2.4 [fb⁻¹].

8.2.1 Simulated events

Monte Carlo (MC) simulated events are used to model SM background production, SM non-resonant HH signal production. The events were passed through the full ATLAS detector simulation [86] based on GEANT 4 [41]. The effects of multiple interactions in the same and neighbouring bunch crossings (pile-up) were modelled by overlaying each hard-scatter event with minimum-bias events, simulated using the soft quantum chromodynamics (QCD) processes of PYTHIA 8.186 [87] with a set of tuned parameters called the A3 tune [88] and the NNPDF2.3_{LO} [89] parton distribution function (PDFs). The EvtGen program [90] was used to model the decays of bottom and charm hadrons in all samples of simulated events, except those generated using Sherpa [91]. The samples generated with SHERPA used the bottom- and charm-hadron decay model implemented within generator. The simulated events were processed through the same reconstruction algorithms as the data. For all samples containing a SM Higgs boson, its mass was fixed to 125 [GeV]. The same mass value is used in the calculation of the Higgs boson decay branching fractions and in the calculation of the single-Higgs-boson and SM non-resonant HH production cross-sections. A summary of the event samples used for the simulation of the signal and background processes is shown in Table 3.

Nowadays, Events containing a W or Z boson produced in association with jets, diboson (WW, WZ and ZZ) production processes and the $t\bar{t}Z$ production process were simulated with the SHERPA 2.2.1 generator [91], whereas the $t\bar{t}W$ production process was simulated with the SHERPA 2.2.8 generator. These samples used the NNPDF3.0_{NNLO} PDF set with dedicated parton shower tuning developed by the SHERPA authors⁵.

8.2.2 Technical improvement performed

Over the samples for W,Z and $t\bar{t}$ di-leptonic was performed an improvement over the main source of Di-Higgs production for $b\bar{b}\tau_{lep}\tau_{had}$ channel, thanks to software development used to search missing file over the repository. Each background sample belongs from a central source managed in a network grid, a central cluster with all the information of all the samples used in ATLAS experiment. Therefore, a software development was implemented that linked the information at the main repository of the channel (from the current server) and the information retrieve from general cluster. Then, with all the information in hand another file works for repair all the existing missing files, for all the regions under analysis (SR,CR,Inv,InvCR). This process affected only those samples that have the SHERPA 2.2.11 [93] and $t\bar{t}$ di-leptonic. One of the most significant improvements is to obtain more statistics, that is, increase the events and also decrease the statistical error. All this at the service of the current studies carried out.

Part of the studies benefited from this work are for example, κ_λ studies, where all the combination of the cross section values, fits over the MC samples and the calculation of the SM limits plays a main role. Another scope of this, could be the scale factor calculation and a better handling of uncertain statistics in this sensitive channel. Without going any further, two milestones drawn with the old samples and the new samples for the mentioned bosons are presented from the next histograms. A summary of the intervened samples are presented below.

⁵ More detail in [92]

Boson	decay
W	$W_{e\nu}$
	$W_{\mu\nu}$
	$W_{\tau\nu}$
Z	Z_{ee}
	$Z_{\mu\nu}$
	$Z_{\tau\tau}$
ttbardilep	-

Pre-fit input variable distributions in the di-Higgs $b\bar{b}\tau_{lep}\tau_{had}$ SLT signal region.

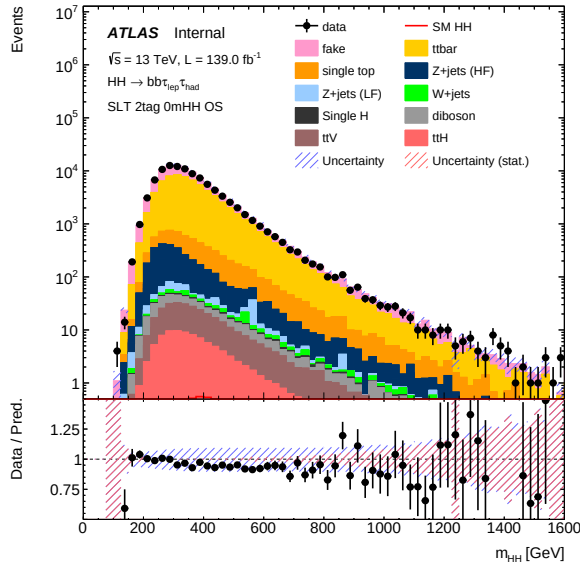


Figure 67: m_{HH} v/s Events.
Baseline samples

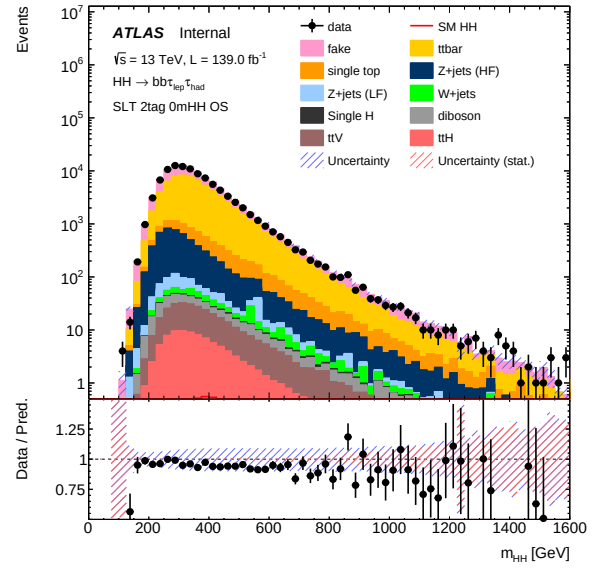


Figure 68: m_{HH} v/s Events.
New Sherpa samples

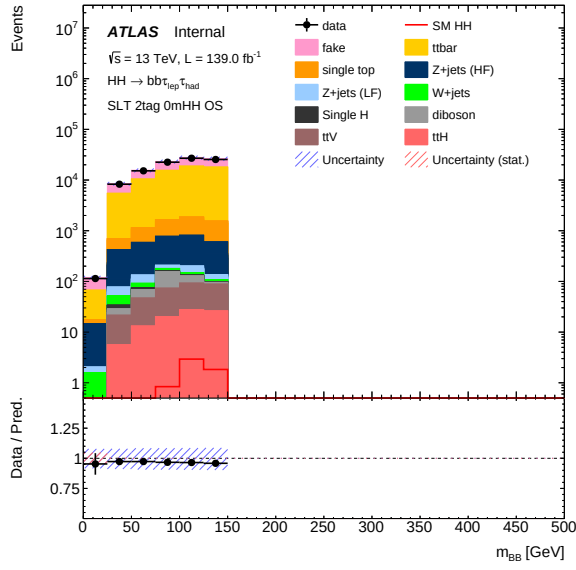


Figure 69: m_{BB} v/s Events.
Baseline samples

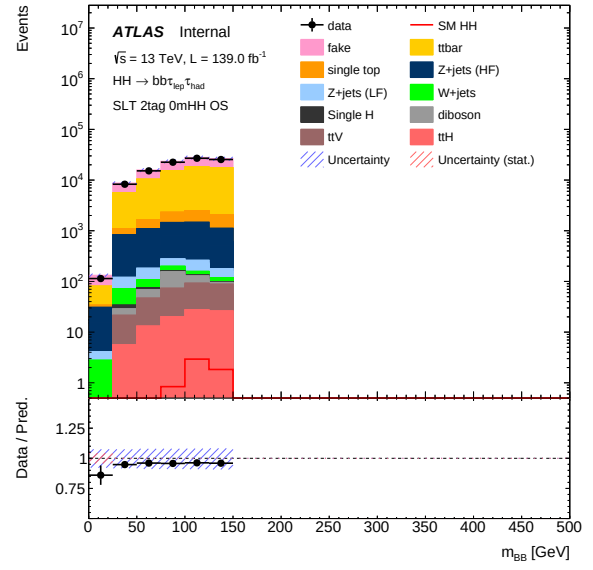


Figure 70: m_{BB} v/s Events.
New Sherpa samples

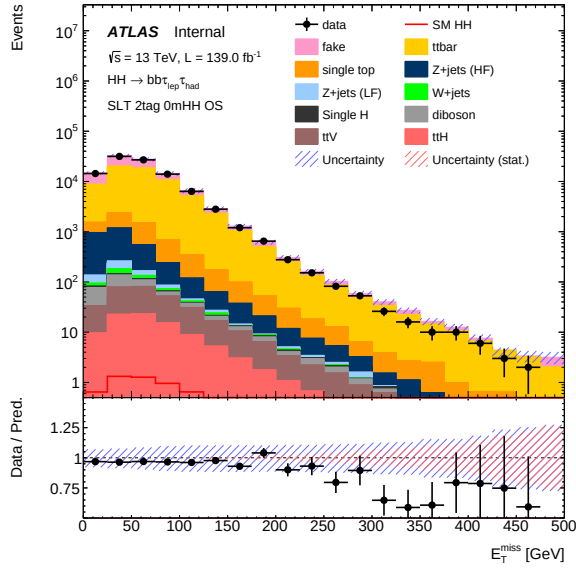


Figure 71: MET v/s Events.
Baseline samples

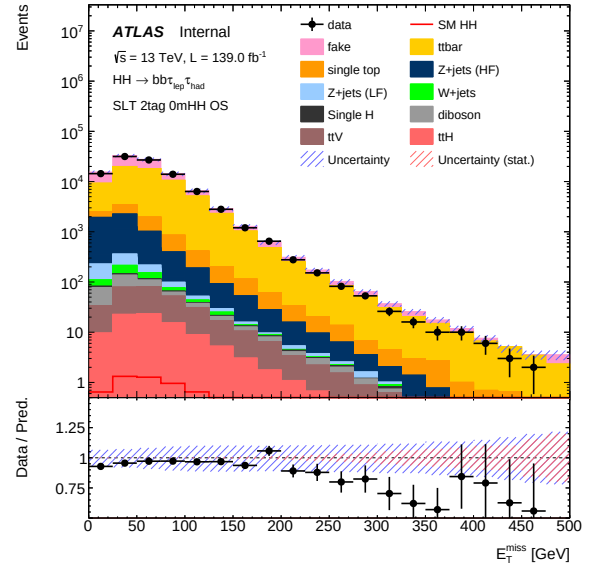


Figure 72: MET v/s Events.
New Sherpa samples

Pre-fit input variable distributions in the di-Higgs $b\bar{b}\tau_{lep}\tau_{had}$ LTT signal region.

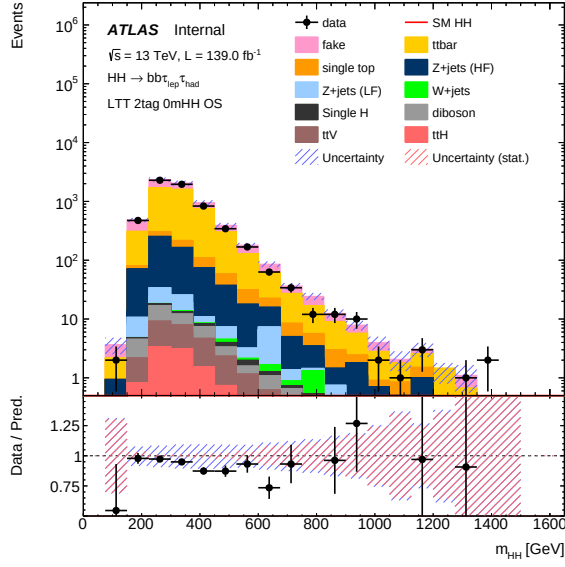


Figure 73: m_{HH} v/s Events.
Baseline samples

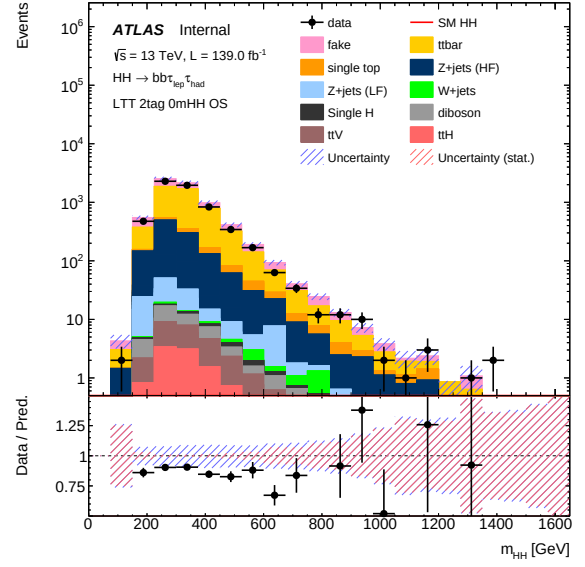


Figure 74: m_{HH} v/s Events.
New Sherpa samples

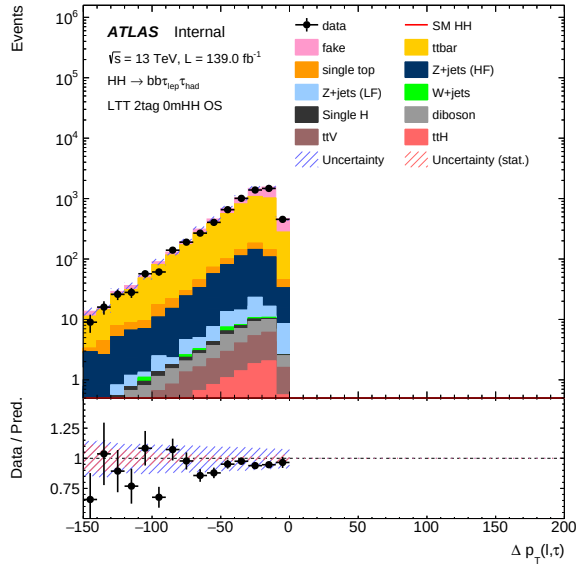


Figure 75: $\Delta P_t(l, \tau)$ v/s Events.
Baseline samples

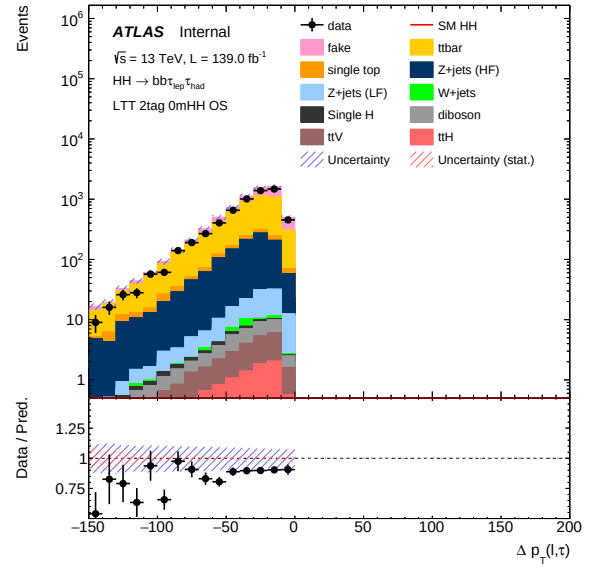


Figure 76: $\Delta P_t(l, \tau)$ v/s Events.
New Sherpa samples

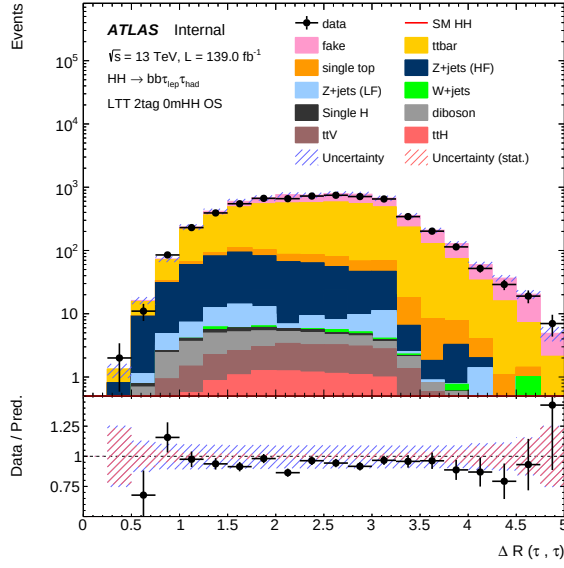


Figure 77: $\Delta R(\tau, \tau)$ v/s Events.
Baseline samples

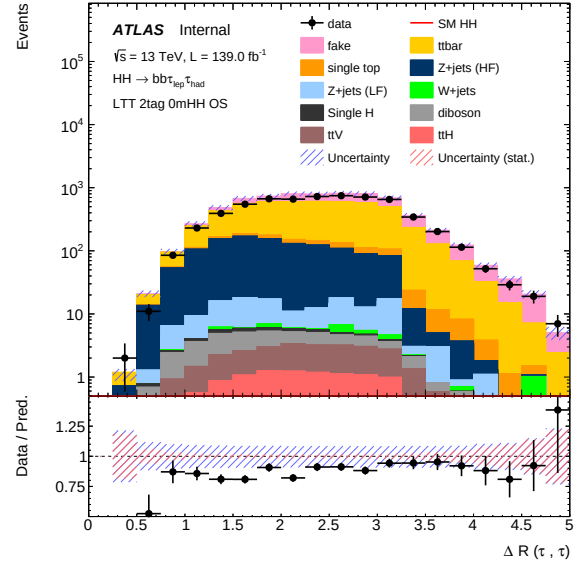


Figure 78: $\Delta R(\tau, \tau)$ v/s Events.
New Sherpa samples

The differences pre-fit modelling histograms shows an increase of the background associated to the new samples involves, it means Z and W, independent of the drawn kinematic variable for SLT and LTT cases. All the baseline pre-fit histograms follow a similar behavior in post-fit Histograms of the internal note [94]. However, the new samples histograms shows a greater miscalculation between bins in signal data and background, due to the increase of statics the new samples grant. This is what the uncertainty graphs show under each histogram. To fix this problem, probability techniques are needed. The studies related to the better scale factor and other analysis are recently started. So, the improvement of the extend the range of the number of possibles samples for the Di-Higgs production in the $b\bar{b}\tau_{lep}\tau_{had}$ channel is beneficial for the improvement of the parameters and limits obtained in this study in this moment.

9 Conclusion

This thesis is composed of different works related to the ATLAS experiment. But, the main focus is dedicated to the trigger system of the experiment that was an important part in obtaining The Qualification Work. On the other hand, An analysis and implementation was intended for the decay of Higgs pairs for the non-resonant channel $b\bar{b}\tau_{lep}\tau_{had}$, which implied a significant improvement for the studies related to this channel, enlarging the study bandwidth for comparison and in the search for better results than the current limits, as for example, in the studies of kappa-lambda in this and other channels.

Within the performance that was carried out for the taus trigger system, there is the correct application in the calculation of efficiency of the kinematic variables, improvements in the internal structure delivered by the software, accompanied by adequate monitoring and analysis that will be important, for the good performance in delivering good candidates for the tau particle. Different chains with different requirements and performances were evaluated, as well as physical and computer filters such as the use of neural networks (RNN) or boosted decision trees (BDT) in track classification and new associated algorithms studied at the time. Added to everything, an analysis was made at the level of simulated events for Di-tau chains later associated by other groups to studies beyond the standard model. Its correct implementation, distribution of its curves associated with its kinematic variables and the understanding of these and the new variables associated with this system, also included a meticulous analysis, such as the monitoring of histograms of variable profiles, histograms of efficiencies and of events, discussed in groups.

Finally, two others jobs was done. The first in DQ for the taus trigger, the information of more than 200 folders with data was analyzed and compared. A comparison with the chi-square test of independence was performed to find the most similar curves, and with this to find a new reference inside this several data raw. Second, an intense searching of the missing CxAOD samples of simulated event for the later studies in the Higgs pair production. A script was performed to recover these samples, and a small analysis was conducted, where it obtained more statistics and better performance using suitable updated samples that utilize a newer version of their generator.

Counting on a broad analysis of the entire ATLAS experiment, a multidisciplinary work was carried out covering various scenarios and special aspects of it. In fact, the work performed in this paper can be used as the basis for various further studies, deeper work on theories related to the Standard Model and those beyond the Standard Model.

Acknowledgements

Thanks to the family and CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; Norwegian Financial Mechanism 2014-2021, Norway; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [95].

Appendix

A Beyond the Standard Model theories

A.1 Supersymmetry

This is a brief summary of the BSM theories following the section 1.5.

The supersymmetry (SUSY) theory [94] is one of the BSM theories that could give a solution to some of the SM limitations described above (hierarchy problem, unification and dark matter). The basic concept of the theory is to relate fermions and bosons by introducing new operators that turn fermionic states in bosonic states and vice versa. This extension predicts the existence of new particles which are supersymmetric partners of the SM ones and differ from them in spin by $1/2$.

In the minimal SUSY extension of the SM, called the MSSM (Minimal Supersymmetric Standard Model) [96], the minimum number of the new particles of the new particles (superparticles) and new interactions, consistent with the existence of supersymmetry, is realised. In this model all the particles are organised in doublets, vector superfields, containing the vector boson and their superpartners, and chiral superfields, containing the fermions and their superpartners. Squarks and sleptons are the scalar superpartners of the SM quarks and leptons. Gauginos are the fermionic superpartners of the SM gauge fields: the gluino is the superpartner of the gluon, three winos correspond to the superpartners of the three $SU(2)_L$ gauge fields and one bino to the $U(1)$ gauge field of the electroweak theory. Concerning the Higgs boson, the simplest theory is one with two Higgs superpartners, the higgsinos, and therefore two scalar Higgs doublets in order to generate the fermionic masses for both up-type and down-type quarks. For this reason the MSSM is also known as a two-Higgs-doublet model (2HDM). The higgsinos, winos and bino mix with each other result in six physical states: four neutralinos, which are electrically neutral fermions.

- Hierarchy problem: in a supersymmetric theory the Planck-scale quantum corrections to the Higgs mass cancel between particles and superparticles, eliminating the naturalness problem.
- Unification: in a supersymmetric theory the running of the gauge coupling constants are modified and precise high energy unification of the coupling is achieved at the energy scale $O(10^{16} \text{ [GeV]})$.
- Dark matter: the lightest neutralino is stable particle and it is a weakly interactive massive particle, thus it is a good dark matter candidate.

A.2 The two-Higgs-doublet model (2HDM)

Two-Higgs-doublet models (2HDM) [97] are models that predict the existence of two scalar Higgs doublets like the MSSM:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \quad (72)$$

with the minimum of the potential corresponding to

$$\Phi_{1,0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \quad \Phi_{2,0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix} . \quad (73)$$

with two complex scalar $SU(2)$ doublets there are eight fields:

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (\nu_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix} \quad (74)$$

with $a=1,2$. Three of those get absorbed to give mass to the $W^\pm$ and Z gauge bosons as in the SM and the remaining are five physical Higgs fields. There are two CP-even neutral scalars (H and h , with h being the lightest CP-even Higgs boson corresponding to the observed Higgs boson with $m = 125$ [GeV]), two charged scalar ($H^\pm$) and one CP-odd neutral pseudo-scalar (A). such a model can thus be described in terms of six parameters: four Higgs masses ($m_H, m_h, m_{H^\pm}, m_A$), the ratio of the two vacuum expectation values ($\tan \beta \nu_1/\nu_2$) and the mixing angle (α) which diagonalizes the mass matrix of the neutral CP-even Higgs bosons.

In this thesis work the search for Higgs boson pair production is also performed as a search for resonant production via ggF of a heavy neutral CP-even scalar Higgs boson of the "HDM model, decaying into a pair of SM Higgs boson, to set limits on its mass in the MSSM.

A.3 Extra dimensions

Extra dimensions models [98] can also address some of the SM problems (hierarchy problem and gravity). In these models, additional space dimensions are included beyond the (3+1) observed space-time dimensions. The assumption is that the fields of the Standard Model are confined to a four-dimensional membrane, while gravity propagates in the additional spatial dimensions. The existence of additional n -dimensions implies that the effective Planck scale observed in 4-dimensions, $\bar{M}_{PL} = M_{PL}/2\pi$ can be seen as the product of M and the volume of the compact space V_n :

$$\bar{M}_{PL}^2 = V_n M^{2+n} . \quad (75)$$

if the radius of the compact space is large enough (large extra dimensions, LED), the fundamental Planck scale can be around the electroweak scale and the hierarchy problem is solved (i.e $M \sim O(TeV)$). But, in this type of models the hierarchy problem between the Higgs boson mass scale and the Planck scale is solved, however a new hierarchy problem is introduced between the radius of the compact space which needs to be very large, and the fundamental Planck scale ($R^{-1} \sim O(MeV)$ and $M \sim O(TeV)$). This problem is solved by introducing warped extra dimensions as in the Randall-Sundrum model.

A.3.1 Randall-Sundrum model

The Randall-Sundrum (RS) model [99] is an extra dimension model with only one additional warped extra dimension, more concretely a 5-dimensional anti-de Sitter space (AdS5) model. In this model the metric is not factorable, but rather the four-dimensional metric is multiplied by a warp factor which is a rapidly changing function of the additional dimension:

$$ds^2 = e^{-2kR_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu + R_c^2 d\phi^2, \quad (76)$$

where $k \sim O(M_{PL})$ is the curvature scale of the space, R_c is the compactification radius, ϕ is the coordinate of the extra dimension with $0 \leq \phi \leq \pi$, $\eta_{\mu\nu}$ is the ordinary Minkowski metric and x^μ are the coordinate for the familiar four dimensions. The additional dimension is compact and has periodic boundary conditions in ϕ given by the identification of (x, ϕ) with $(x, -\phi)$. At fixed points $\phi = 0$ and $\phi = \pi$ there are the Planck brane and the TeV brane respectively, meaning that on the each of these boundaries stands a four dimensional world like the one we live in. It is assumed that gravity propagates in the whole bulk while the SM fields are localised in the TeV brane. The hierarchy between the Planck scale and the electroweak scale is given by the exponential warp factor via the relationship:

$$M_{PL} e^{-kR_c\pi} \sim O(TeV), \quad (77)$$

requiring not too large R_c to generate a large hierarchy since the source of the hierarchy is an exponential function of the compactification radius. The small exponential factor above $O(10^{-16})$ is the source of the large hierarchy between the observed Planck and weak scales. A scheme of the 5-dimensional space of the RS theory is illustrated in Figure 79.

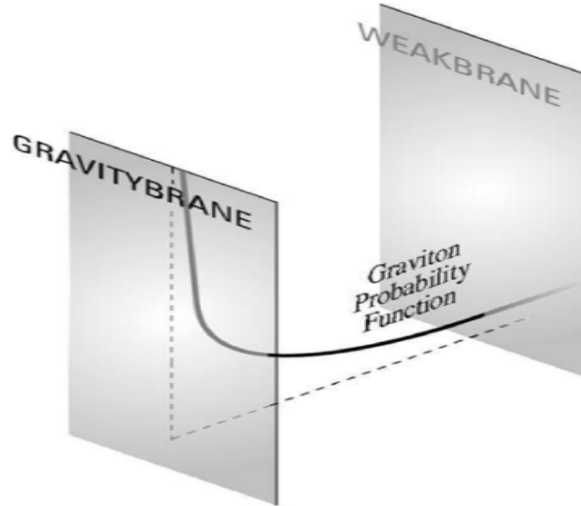


Figure 79: Scheme of the 5-dimensional space of the RS theory. The gravity (Planck) and weak (TeV) branes are the 4-dimensional boundaries of the extra dimension. The figure also illustrates the metric behaviour along the extra dimension [100].

To explore the gravity effects on the TeV brane at $\phi = \pi$, the graviton field can be expanded, treated as small fluctuations around the background metric, into the RS Kaluza-Klein (KK) modes $h_{\mu\nu}^n(x)$ upon compactification. Then, the effective 4-dimensional interaction Lagrangian of the RS model is given by:

$$\mathcal{L} = -\frac{1}{\bar{M}_{PL}} T^{\mu\nu} h_{\mu\nu}^0(x) - \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h_{\mu\nu}^n, \quad (78)$$

where $\Lambda_\pi = \bar{M}_{PL} e^{-kR_c \pi}$ and $T^{\mu\nu}$ represents the SM energy-momentum tensor. The couplings of the zero mode ($n=0$), which is massless, and massive modes ($n = 1, 2, \dots$) to the SM particles are proportional to $\frac{1}{\bar{M}_{PL}}$ and $\frac{1}{\Lambda_\pi}$ respectively. The mass of the n^{th} RS KK graviton excitation can be written as:

$$\Gamma_n = \frac{1}{16\pi} x_n^2 M_n c^2 \Delta_n, \quad (79)$$

where $\Delta_n = \sum_V \Delta_n^{VV} + \sum_f \Delta_n^{HH}$ and Δ_n^{yy} is the coefficient for the decay $G_{kk}^n \rightarrow yy$, with y being production via ggF of a spin-2 graviton excitation G_{KK} in the bulk RS model, decaying into a pair of SM Higgs boson, to set limits on its mass.

A.4 Leptoquarks

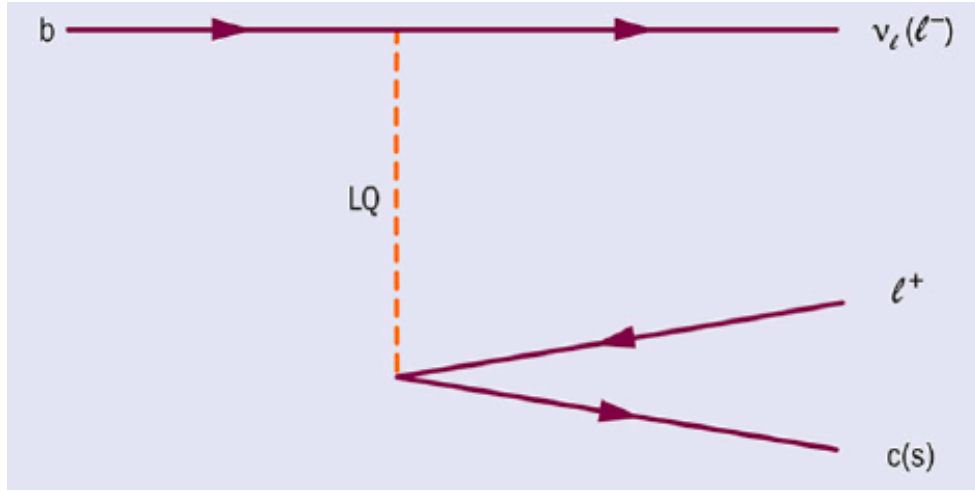


Figure 80: Example of a Feynman diagram of a possible leptoquark-mediated $b \rightarrow c\ell^+\nu$ or $b \rightarrow s\ell^+\ell^-$ transition.

Leptoquarks (LQ) [101] are predicted by many extensions of the SM, such as GUTs, technicolor and composite models, and provide a connection between the quark and lepton sectors which exhibit a similar structure in the SM. LQs can be scalar or vector bosons, with masses predicted at the TeV scale. They carry colour charge and fractional electric charge and possess both non-zero baryon and lepton numbers and therefore decay to a quark-lepton pair. They are often assumed to couple to a single generation of quarks and leptons following the minimal Buchmüller-Rückl-Wyler model [102], which is a model-independent approach to classify the production and the decay of LQs.

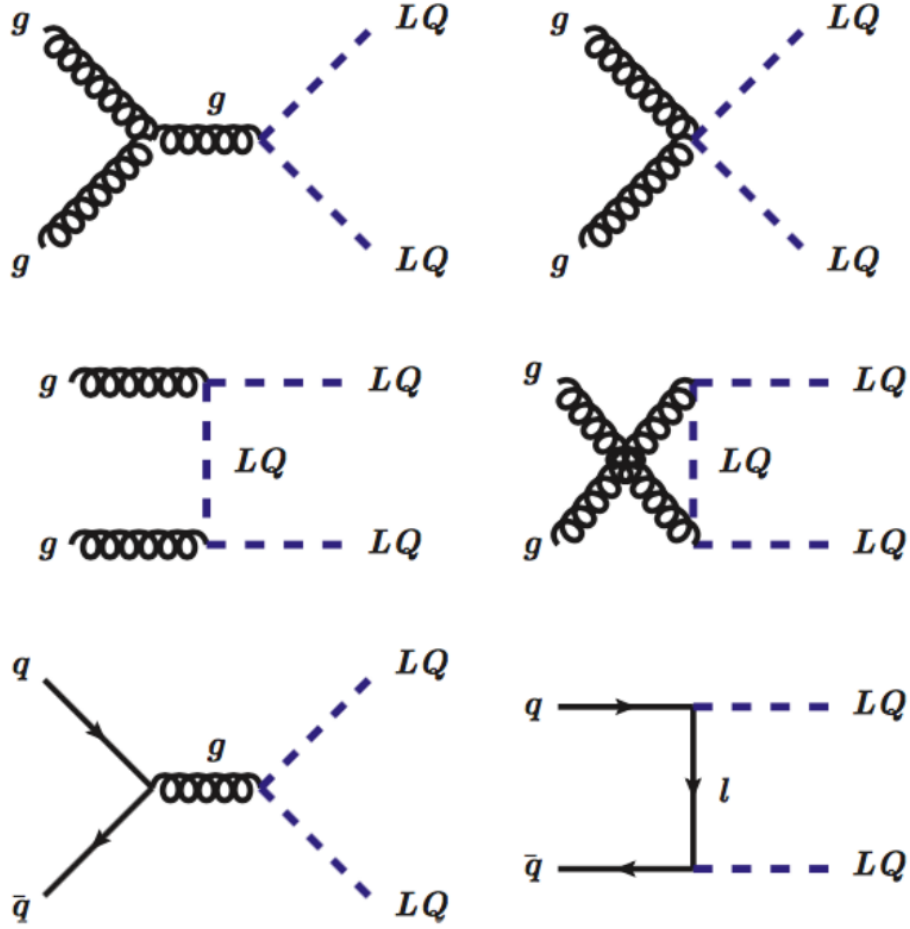


Figure 81: Leading Order Feynman diagrams of LQ pair production.

Recently, anomalies have been observed in B-meson decays giving a hint of possible violation of lepton universality. They could be attributed, if confirmed, to the exchange of LQs. Particularly, anomalies in the ratio of the B-meson decay rate to τ -leptons and to muon have been observed by the BarBar, Belle and LHCb experiments with deviations from SM of the order of four standard deviations. In order to explain these anomalies, flavour structure studies of LQ coupling have been performed, which show that predominant coupling to third-generation fermions are required. Moreover, anomalies in the ratio not the B-meson decay rate to muons and to electrons observed by the LHCb collaboration could also be explained in a specific composite model, which predicts LQs decaying predominantly to third-generation fermions and LQs with masses around the TeV scale. Figure 81 shows an example of a Feynman diagram of a possible leptoquark-mediated $b \rightarrow cl^+\nu_l$ or $b \rightarrow sl^+l^-$ transition, that could explain the anomalies observed in the B-meson decays. This motivates the interest in the search for third-generation LQs.

In pp collisions, LQs can be produced in pairs predominantly through gluon-gluon fusion or quark-antiquark annihilation processes. Feynman diagrams of such processes are shown in Figure 81. Third-generation LQs

(LQ_3) can decay to $b\tau$ or $t\nu$ in case of up-type LQs (LQ_3^u) and $b\nu$ or $t\tau$ in case of down-type LQs (LQ_3^d), as shown in Figure 82.

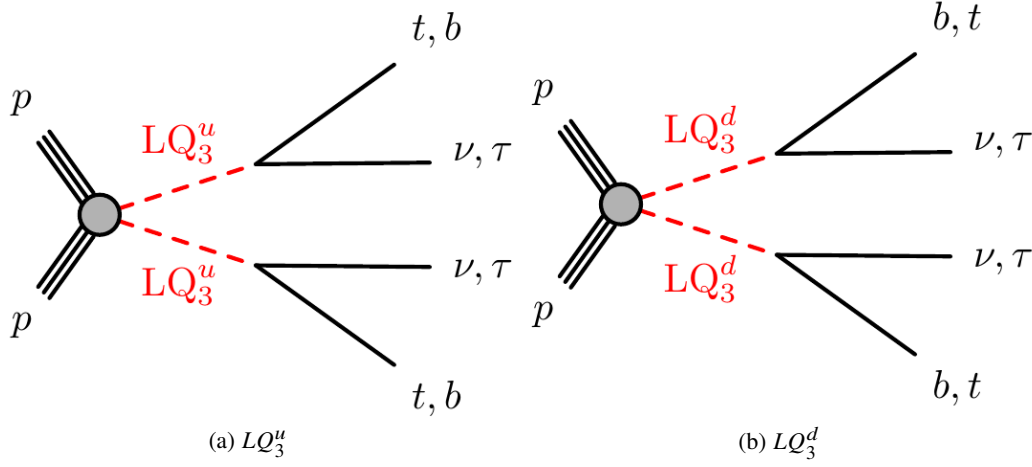


Figure 82: Pair production and decay diagrams of LQs.

References

- [1] D. de Florian et al. ‘Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector’. In: (2016). doi: [10.23731/CYRM-2017-002](https://doi.org/10.23731/CYRM-2017-002). arXiv: [1610.07922 \[hep-ph\]](https://arxiv.org/abs/1610.07922). URL: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG>.
- [2] L. H. C. S. W. Group. *LHC Higgs Cross Section Working Group web page*. 2016. URL: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG?redirectedfrom=LHCPhysics.LHCHXSWG>.
- [3] S. Borowka et al. ‘Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence’. In: *Phys. Rev. Lett.* 117 (1 June 2016), p. 012001. doi: [10.1103/PhysRevLett.117.012001](https://doi.org/10.1103/PhysRevLett.117.012001). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.117.012001>.
- [4] S. Borowka et al. ‘Full top quark mass dependence in Higgs boson pair production at NLO’. In: *Journal of High Energy Physics* 2016.10 (Oct. 2016). doi: [10.1007/jhep10\(2016\)107](https://doi.org/10.1007/jhep10(2016)107). URL: <https://doi.org/10.1007%5C%2Fjhep10%5C%282016%5C%29107>.
- [5] ATLAS Collaboration. ‘The ATLAS Experiment at the CERN Large Hadron Collider’. In: *JINST* 3 (2008), S08003. doi: [10.1088/1748-0221/3/08/S08003](https://doi.org/10.1088/1748-0221/3/08/S08003).
- [6] J. J. T. M. F.R.S. ‘XL. Cathode Rays’. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 44.269 (1897), pp. 293–316. doi: [10.1080/14786449708621070](https://doi.org/10.1080/14786449708621070). eprint: <https://doi.org/10.1080/14786449708621070>. URL: <https://doi.org/10.1080/14786449708621070>.
- [7] N. Bohr and D. phil. ‘I. On the constitution of atoms and molecules’. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 26.151 (1913), pp. 1–25. doi: [10.1080/14786441308634955](https://doi.org/10.1080/14786441308634955). eprint: <https://doi.org/10.1080/14786441308634955>. URL: <https://doi.org/10.1080/14786441308634955>.

- [8] N. P. Samios. ‘Early baryon and meson spectroscopy culminating in the discovery of the Omega minus SU(3) and quarks’. In: (June 1993). URL: <https://www.osti.gov/biblio/10162083>.
- [9] P. W. Higgs. ‘Broken Symmetries and the Masses of Gauge Bosons’. In: *Phys. Rev. Lett.* 13 (16 Nov. 1964), pp. 508–509. DOI: [10.1103/PhysRevLett.13.508](https://doi.org/10.1103/PhysRevLett.13.508). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.508>.
- [10] F. Englert and R. Brout. ‘Broken Symmetry and the Mass of Gauge Vector Mesons’. In: *Phys. Rev. Lett.* 13 (9 Aug. 1964), pp. 321–323. DOI: [10.1103/PhysRevLett.13.321](https://doi.org/10.1103/PhysRevLett.13.321). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.321>.
- [11] ATLAS Collaboration. ‘Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC’. In: *Phys. Lett. B* 716 (2012), p. 1. DOI: [10.1016/j.physletb.2012.08.020](https://doi.org/10.1016/j.physletb.2012.08.020). arXiv: [1207.7214](https://arxiv.org/abs/1207.7214) [hep-ex].
- [12] CMS Collaboration. ‘Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC’. In: *Phys. Lett. B* 716 (2012), p. 30. DOI: [10.1016/j.physletb.2012.08.021](https://doi.org/10.1016/j.physletb.2012.08.021). arXiv: [1207.7235](https://arxiv.org/abs/1207.7235) [hep-ex].
- [13] J. Ellis. ‘Higgs Physics’. In: (2015). 52 pages, 45 figures, Lectures presented at the ESHEP 2013 School of High-Energy Physics, to appear as part of the proceedings in a CERN Yellow Report, pp. 117–168. DOI: [10.5170/CERN-2015-004.117](https://doi.org/10.5170/CERN-2015-004.117). arXiv: [1312.5672](https://arxiv.org/abs/1312.5672). URL: <https://cds.cern.ch/record/1638469>.
- [14] ATLAS and CMS Collaborations. ‘Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments’. In: *Phys. Rev. Lett.* 114 (2015), p. 191803. DOI: [10.1103/PhysRevLett.114.191803](https://doi.org/10.1103/PhysRevLett.114.191803). arXiv: [1503.07589](https://arxiv.org/abs/1503.07589) [hep-ex].
- [15] ATLAS Collaboration. ‘Evidence for the spin-0 nature of the Higgs boson using ATLAS data’. In: *Phys. Lett. B* 726 (2013), p. 120. DOI: [10.1016/j.physletb.2013.08.026](https://doi.org/10.1016/j.physletb.2013.08.026). arXiv: [1307.1432](https://arxiv.org/abs/1307.1432) [hep-ex].
- [16] ATLAS Collaboration. ‘Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector’. In: *Phys. Rev. D* 91 (2015), p. 012006. DOI: [10.1103/PhysRevD.91.012006](https://doi.org/10.1103/PhysRevD.91.012006). arXiv: [1408.5191](https://arxiv.org/abs/1408.5191) [hep-ex].
- [17] ATLAS Collaboration. ‘Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC’. In: *Phys. Lett. B* 726 (2013), p. 88. DOI: [10.1016/j.physletb.2013.08.010](https://doi.org/10.1016/j.physletb.2013.08.010). arXiv: [1307.1427](https://arxiv.org/abs/1307.1427) [hep-ex]. Erratum: in: *Phys. Lett. B* 734 (2014), p. 406. DOI: [10.1016/j.physletb.2014.05.011](https://doi.org/10.1016/j.physletb.2014.05.011).
- [18] ATLAS Collaboration. ‘Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector’. In: *Phys. Rev. D* 92 (2015), p. 012006. DOI: [10.1103/PhysRevD.92.012006](https://doi.org/10.1103/PhysRevD.92.012006). arXiv: [1412.2641](https://arxiv.org/abs/1412.2641) [hep-ex].
- [19] ATLAS Collaboration. ‘Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector’. In: *Phys. Lett. B* 784 (2018), p. 173. DOI: [10.1016/j.physletb.2018.07.035](https://doi.org/10.1016/j.physletb.2018.07.035). arXiv: [1806.00425](https://arxiv.org/abs/1806.00425) [hep-ex].
- [20] ATLAS Collaboration. ‘Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector’. In: *Phys. Lett. B* 786 (2018), p. 59. DOI: [10.1016/j.physletb.2018.09.013](https://doi.org/10.1016/j.physletb.2018.09.013). arXiv: [1808.08238](https://arxiv.org/abs/1808.08238) [hep-ex].

- [21] ATLAS Collaboration. ‘Cross-section measurements of the Higgs boson decaying into a pair of τ -leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector’. In: *Phys. Rev. D* 99 (2019), p. 072001. DOI: [10.1103/PhysRevD.99.072001](https://doi.org/10.1103/PhysRevD.99.072001). arXiv: [1811.08856](https://arxiv.org/abs/1811.08856) [hep-ex].
- [22] C. Patrignani. ‘Review of Particle Physics’. In: *Chinese Physics C* 40.10 (Oct. 2016), p. 100001. DOI: [10.1088/1674-1137/40/10/100001](https://doi.org/10.1088/1674-1137/40/10/100001). URL: <https://dx.doi.org/10.1088/1674-1137/40/10/100001>.
- [23] A. Betti et al. *Searches for Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state with 139 fb $^{-1}$ of pp collision data with the ATLAS detector*. Tech. rep. Geneva: CERN, 2020. URL: <https://cds.cern.ch/record/2743097>.
- [24] A. Betti. ‘Search for the Standard Model Higgs boson pair production and new physics phenomena in the $b\bar{b}\tau_{had}^+\tau_{had}^-$ final state with the ATLAS detector’. Presented 31 Jul 2019. 2019. URL: <https://cds.cern.ch/record/2699449>.
- [25] B. Dumont, K. Nishiwaki and R. Watanabe. ‘LHC constraints and prospects for S_1 scalar leptoquark explaining the $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ anomaly’. In: *Phys. Rev. D* 94 (3 Aug. 2016), p. 034001. DOI: [10.1103/PhysRevD.94.034001](https://doi.org/10.1103/PhysRevD.94.034001). URL: <https://link.aps.org/doi/10.1103/PhysRevD.94.034001>.
- [26] R. Aaij et al. ‘Test of Lepton Universality Using $B^+ \rightarrow K^+\ell^+\ell^-$ Decays’. In: *Phys. Rev. Lett.* 113 (15 Oct. 2014), p. 151601. DOI: [10.1103/PhysRevLett.113.151601](https://doi.org/10.1103/PhysRevLett.113.151601). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.113.151601>.
- [27] ATLAS Collaboration. *ATLAS Detector and Physics Performance: Technical Design Report, Volume 1*. ATLAS-TDR-14; CERN-LHCC-99-014. 1999. URL: <https://cds.cern.ch/record/391176>.
- [28] ATLAS Collaboration. *ATLAS Detector and Physics Performance: Technical Design Report, Volume 2*. ATLAS-TDR-15; CERN-LHCC-99-015. 1999. URL: <https://cds.cern.ch/record/391177>.
- [29] L. Evans and P. Bryant. ‘LHC Machine’. In: *JINST* 3 (2008), S08001. DOI: [10.1088/1748-0221/3/08/S08001](https://doi.org/10.1088/1748-0221/3/08/S08001).
- [30] CMS Collaboration. ‘The CMS experiment at the CERN LHC’. In: *JINST* 3 (2008), S08004. DOI: [10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).
- [31] T. A. Collaboration et al. ‘The ALICE experiment at the CERN LHC’. In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08002. DOI: [10.1088/1748-0221/3/08/S08002](https://doi.org/10.1088/1748-0221/3/08/S08002). URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08002>.
- [32] T. L. Collaboration et al. ‘The LHCb Detector at the LHC’. In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08005. DOI: [10.1088/1748-0221/3/08/S08005](https://doi.org/10.1088/1748-0221/3/08/S08005). URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08005>.
- [33] T. T. Collaboration et al. ‘The TOTEM Experiment at the CERN Large Hadron Collider’. In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08007. DOI: [10.1088/1748-0221/3/08/S08007](https://doi.org/10.1088/1748-0221/3/08/S08007). URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08007>.
- [34] T. L. Collaboration et al. ‘The LHCf detector at the CERN Large Hadron Collider’. In: *Journal of Instrumentation* 3.08 (Aug. 2008), S08006. DOI: [10.1088/1748-0221/3/08/S08006](https://doi.org/10.1088/1748-0221/3/08/S08006). URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08006>.
- [35] A. Collaboration. *Luminosity Public Result*. 2018. URL: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>.

- [36] A. Collaboration. *Luminosity Public Result*. 2022. URL: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3>.
- [37] LHC. *High Luminosity LHC Project*. URL: <https://hilumilhc.web.cern.ch>.
- [38] J. C. Collins and D. E. Soper. ‘Parton distribution and decay functions’. In: *Nuclear Physics B* 194.3 (1982), pp. 445–492. ISSN: 0550-3213. DOI: [https://doi.org/10.1016/0550-3213\(82\)90021-9](https://doi.org/10.1016/0550-3213(82)90021-9). URL: <https://www.sciencedirect.com/science/article/pii/0550321382900219>.
- [39] A. D. Martin et al. ‘Parton distributions for the LHC’. In: *The European Physical Journal C* 63.2 (July 2009), pp. 189–285. DOI: [10.1140/epjc/s10052-009-1072-5](https://doi.org/10.1140/epjc/s10052-009-1072-5). URL: <https://doi.org/10.1140%5C%2Fepjc%5C%2Fs10052-009-1072-5>.
- [40] G. Altarelli and G. Parisi. ‘Asymptotic freedom in parton language’. In: *Nuclear Physics B* 126.2 (1977), pp. 298–318. ISSN: 0550-3213. DOI: [https://doi.org/10.1016/0550-3213\(77\)90384-4](https://doi.org/10.1016/0550-3213(77)90384-4). URL: <https://www.sciencedirect.com/science/article/pii/0550321377903844>.
- [41] S. Agostinelli et al. ‘Geant4—a simulation toolkit’. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 506.3 (2003), pp. 250–303. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8). URL: <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [42] G. Aad et al. ‘The ATLAS Simulation Infrastructure. The ATLAS Simulation Infrastructure’. In: *Eur. Phys. J. C* 70 (2010). Submitted to Eur. Phys. J. C, pp. 823–874. DOI: [10.1140/epjc/s10052-010-1429-9](https://doi.org/10.1140/epjc/s10052-010-1429-9). arXiv: [1005.4568](https://arxiv.org/abs/1005.4568). URL: <https://cds.cern.ch/record/1267853>.
- [43] J. Alwall et al. ‘MadGraph 5: going beyond’. In: *Journal of High Energy Physics* 2011.6 (June 2011). DOI: [10.1007/jhep06\(2011\)128](https://doi.org/10.1007/jhep06(2011)128). URL: <https://doi.org/10.1007%5C%2Fjhep06%5C%282011%5C%29128>.
- [44] J. Alwall et al. ‘The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations’. In: *Journal of High Energy Physics* 2014.7 (July 2014). DOI: [10.1007/jhep07\(2014\)079](https://doi.org/10.1007/jhep07(2014)079). URL: <https://doi.org/10.1007%5C%2Fjhep07%5C%282014%5C%29079>.
- [45] S. Alioli et al. ‘A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX’. In: *Journal of High Energy Physics* 2010.6 (June 2010). DOI: [10.1007/jhep06\(2010\)043](https://doi.org/10.1007/jhep06(2010)043). URL: <https://doi.org/10.1007%5C%2Fjhep06%5C%282010%5C%29043>.
- [46] T. Gleisberg et al. ‘Event generation with SHERPA 1.1’. In: *Journal of High Energy Physics* 2009.02 (Feb. 2009), pp. 007–007. DOI: [10.1088/1126-6708/2009/02/007](https://doi.org/10.1088/1126-6708/2009/02/007). URL: <https://doi.org/10.1088%5C%2F1126-6708%5C%2F2009%5C%2F02%5C%2F007>.
- [47] T. Sjöstrand, S. Mrenna and P. Skands. ‘PYTHIA 6.4 physics and manual’. In: *Journal of High Energy Physics* 2006.05 (May 2006), pp. 026–026. DOI: [10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026). URL: <https://doi.org/10.1088%5C%2F1126-6708%5C%2F2006%5C%2F05%5C%2F026>.
- [48] T. Sjöstrand et al. ‘An introduction to PYTHIA 8.2’. In: *Computer Physics Communications* 191 (June 2015), pp. 159–177. DOI: [10.1016/j.cpc.2015.01.024](https://doi.org/10.1016/j.cpc.2015.01.024). URL: <https://doi.org/10.1016%5C%2Fj.cpc.2015.01.024>.

- [49] M. Bähr et al. ‘Herwig ++ physics and manual’. In: *The European Physical Journal C* 58.4 (Nov. 2008), pp. 639–707. DOI: [10.1140/epjc/s10052-008-0798-9](https://doi.org/10.1140/epjc/s10052-008-0798-9). URL: <https://doi.org/10.1140%5C%2Fepjc%5C%2Fs10052-008-0798-9>.
- [50] J. Pequenaio. ‘Computer generated image of the whole ATLAS detector’. 2008. URL: <https://cds.cern.ch/record/1095924>.
- [51] N. Ilic. ‘Observation of the Higgs Boson decaying to $WW^* \rightarrow l \nu \nu$ ’. In: 2015.
- [52] ATLAS Collaboration. *ATLAS Magnet System: Magnet Project Technical Design Report, Volume 1*. ATLAS-TDR-6; CERN-LHCC-97-018. 1997. URL: <https://cds.cern.ch/record/338080>.
- [53] ATLAS Collaboration. *ATLAS Inner Detector: Technical Design Report, Volume 1*. ATLAS-TDR-4; CERN-LHCC-97-016. 1997. URL: <https://cds.cern.ch/record/331063>.
- [54] ATLAS Collaboration. *ATLAS Inner Detector: Technical Design Report, Volume 2*. ATLAS-TDR-5, CERN-LHCC-97-017. 1997. URL: <https://cds.cern.ch/record/331064>.
- [55] J. Pequenaio. ‘Computer generated image of the ATLAS inner detector’. 2008. URL: <https://cds.cern.ch/record/1095926>.
- [56] ATLAS Collaboration. *ATLAS Calorimeter Performance: Technical Design Report*. ATLAS-TDR-1; CERN-LHCC-96-040. 1996. URL: <https://cds.cern.ch/record/331059>.
- [57] J. Pequenaio. ‘Computer Generated image of the ATLAS calorimeter’. 2008. URL: <https://cds.cern.ch/record/1095927>.
- [58] ATLAS Collaboration. *ATLAS Muon Spectrometer: Technical Design Report*. ATLAS-TDR-10; CERN-LHCC-97-022. CERN, 1997. URL: <https://cds.cern.ch/record/331068>.
- [59] ATLAS Collaboration. ‘Operation of the ATLAS trigger system in Run 2’. In: *JINST* 15 (2020), P10004. DOI: [10.1088/1748-0221/15/10/P10004](https://doi.org/10.1088/1748-0221/15/10/P10004). arXiv: [2007.12539](https://arxiv.org/abs/2007.12539) [hep-ex].
- [60] ATLAS Collaboration. *Trigger Menu in 2018*. ATL-DAQ-PUB-2019-001. 2019. URL: <https://cds.cern.ch/record/2693402>.
- [61] A. Collaboration. *Lowest un-prescaled triggers per data-taking period*. 2022. URL: <https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LowestUnprescaled>.
- [62] A. Collaboration. *Trigger Operation Public Results*. 2022. URL: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults>.
- [63] B. Wynne. ‘Implementation of the ATLAS trigger within the ATLAS Multi Threaded Software Framework AthenaMT’. In: (2016). URL: <https://cds.cern.ch/record/2229581>.
- [64] K. Pearson and U. of London. Department of Applied Statistics. *On the Theory of Contingency and Its Relation to Association and Normal Correlation ; On the General Theory of Skew Correlation and Non-linear Regression*. Drapers’ company research memoirs: Biometric series. Cambridge University Press, 1904. URL: <https://books.google.cl/books?id=j4XjZwEACAAJ>.
- [65] H. Cramér. *Mathematical methods of statistics*. Vol. 26. Princeton university press, 1999.
- [66] S. Dawson, S. Dittmaier and M. Spira. ‘Neutral Higgs-boson pair production at hadron colliders: QCD corrections’. In: *Phys. Rev. D* 58 (11 Nov. 1998), p. 115012. DOI: [10.1103/PhysRevD.58.115012](https://doi.org/10.1103/PhysRevD.58.115012). URL: <https://link.aps.org/doi/10.1103/PhysRevD.58.115012>.
- [67] J. Baglio et al. ‘Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme’. In: *The European Physical Journal C* 79.6 (May 2019). DOI: [10.1140/epjc/s10052-019-6973-3](https://doi.org/10.1140/epjc/s10052-019-6973-3). URL: <https://doi.org/10.1140%5C%2Fepjc%5C%2Fs10052-019-6973-3>.

- [68] D. de Florian and J. Mazzitelli. ‘Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD’. In: *Phys. Rev. Lett.* 111 (20 Nov. 2013), p. 201801. DOI: [10.1103/PhysRevLett.111.201801](https://doi.org/10.1103/PhysRevLett.111.201801). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.111.201801>.
- [69] D. Y. Shao et al. ‘Threshold resummation effects in Higgs boson pair production at the LHC’. In: *Journal of High Energy Physics* 2013.7 (July 2013). DOI: [10.1007/jhep07\(2013\)169](https://doi.org/10.1007/jhep07(2013)169). URL: <https://doi.org/10.1007%5C%2Fjhep07%5C%282013%5C%29169>.
- [70] D. de Florian and J. Mazzitelli. *Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC*. 2015. DOI: [10.48550/ARXIV.1505.07122](https://arxiv.org/abs/1505.07122). URL: <https://arxiv.org/abs/1505.07122>.
- [71] M. Grazzini et al. ‘Higgs boson pair production at NNLO with top quark mass effects’. In: *Journal of High Energy Physics* 2018.5 (May 2018). DOI: [10.1007/jhep05\(2018\)059](https://doi.org/10.1007/jhep05(2018)059). URL: <https://doi.org/10.1007%5C%2Fjhep05%5C%282018%5C%29059>.
- [72] J. Baglio et al. ‘ $gg \rightarrow HH$: Combined uncertainties’. In: *Phys. Rev. D* 103 (5 Mar. 2021), p. 056002. DOI: [10.1103/PhysRevD.103.056002](https://link.aps.org/doi/10.1103/PhysRevD.103.056002). URL: <https://link.aps.org/doi/10.1103/PhysRevD.103.056002>.
- [73] V. Branchina, H. Faivre and V. Pagon. ‘Effective potential and vacuum stability’. In: *Journal of Physics G: Nuclear and Particle Physics* 36.1 (Nov. 2008), p. 015006. DOI: [10.1088/0954-3899/36/1/015006](https://dx.doi.org/10.1088/0954-3899/36/1/015006). URL: <https://dx.doi.org/10.1088/0954-3899/36/1/015006>.
- [74] D. Buttazzo et al. ‘Investigating the near-criticality of the Higgs boson’. In: *Journal of High Energy Physics* 2013.12 (Dec. 2013). DOI: [10.1007/jhep12\(2013\)089](https://doi.org/10.1007/jhep12(2013)089). URL: <https://doi.org/10.1007%5C%2Fjhep12%5C%282013%5C%29089>.
- [75] M. Reichert et al. ‘Probing baryogenesis through the Higgs boson self-coupling’. In: *Phys. Rev. D* 97 (7 Apr. 2018), p. 075008. DOI: [10.1103/PhysRevD.97.075008](https://link.aps.org/doi/10.1103/PhysRevD.97.075008). URL: <https://link.aps.org/doi/10.1103/PhysRevD.97.075008>.
- [76] F. Bezrukov and M. Shaposhnikov. ‘The Standard Model Higgs boson as the inflaton’. In: *Physics Letters B* 659.3 (2008), pp. 703–706. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2007.11.072>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269307014128>.
- [77] I. Masina and A. Notari. ‘Higgs mass range from standard model false vacuum inflation in scalar-tensor gravity’. In: *Phys. Rev. D* 85 (12 June 2012), p. 123506. DOI: [10.1103/PhysRevD.85.123506](https://link.aps.org/doi/10.1103/PhysRevD.85.123506). URL: <https://link.aps.org/doi/10.1103/PhysRevD.85.123506>.
- [78] M. Aaboud et al. ‘Search for Resonant and Nonresonant Higgs Boson Pair Production in the $b\bar{b}\tau^+\tau^-$ Decay Channel in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector’. In: *Phys. Rev. Lett.* 121 (19 Nov. 2018), p. 191801. DOI: [10.1103/PhysRevLett.121.191801](https://link.aps.org/doi/10.1103/PhysRevLett.121.191801). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.121.191801>.
- [79] A. Sirunyan et al. ‘Search for Higgs boson pair production in events with two bottom quarks and two tau leptons in proton–proton collisions at $s=13$ TeV’. In: *Physics Letters B* 778 (2018), pp. 101–127. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2018.01.001>. URL: <https://www.sciencedirect.com/science/article/pii/S037026931830008X>.
- [80] G. Aad et al. ‘Combination of searches for Higgs boson pairs in pp collisions at $s=13$ TeV with the ATLAS detector’. In: *Physics Letters B* 800 (2020), p. 135103. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2019.135103>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269319308251>.

- [81] A. M. Sirunyan et al. ‘Combination of Searches for Higgs Boson Pair Production in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV’. In: *Phys. Rev. Lett.* 122 (12 Mar. 2019), p. 121803. DOI: [10.1103/PhysRevLett.122.121803](https://doi.org/10.1103/PhysRevLett.122.121803). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.122.121803>.
- [82] ‘A portrait of the Higgs boson by the CMS experiment ten years after the discovery’. In: *Nature* 607.7917 (July 2022), pp. 60–68. DOI: [10.1038/s41586-022-04892-x](https://doi.org/10.1038/s41586-022-04892-x). URL: <https://doi.org/10.1038/s41586-022-04892-x>.
- [83] ATLAS Collaboration. *Constraining the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV*. 2022. DOI: [10.48550/ARXIV.2211.01216](https://arxiv.org/abs/2211.01216). URL: <https://arxiv.org/abs/2211.01216>.
- [84] CERN. *CERN Yellow Reports: Monographs, Vol 2 (2017): Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector*. en. 2017. DOI: [10.23731/CYRM-2017-002](https://e-publishing.cern.ch/index.php/CYRM/issue/view/32). URL: <https://e-publishing.cern.ch/index.php/CYRM/issue/view/32>.
- [85] A. Djouadi, J. Kalinowski and M. Spira. ‘HDECAY: a program for Higgs boson decays in the Standard Model and its supersymmetric extension’. In: *Computer Physics Communications* 108.1 (1998), pp. 56–74. ISSN: 0010-4655. DOI: [https://doi.org/10.1016/S0010-4655\(97\)00123-9](https://doi.org/10.1016/S0010-4655(97)00123-9). URL: <https://www.sciencedirect.com/science/article/pii/S0010465597001239>.
- [86] G. Aad et al. ‘The ATLAS Simulation Infrastructure’. In: *Eur. Phys. J. C* 70 (2010), pp. 823–874. DOI: [10.1140/epjc/s10052-010-1429-9](https://arxiv.org/abs/1005.4568). arXiv: [1005.4568](https://arxiv.org/abs/1005.4568) [physics.ins-det].
- [87] T. Sjöstrand, S. Mrenna and P. Skands. ‘A brief introduction to PYTHIA 8.1’. In: *Computer Physics Communications* 178.11 (June 2008), pp. 852–867. DOI: [10.1016/j.cpc.2008.01.036](https://doi.org/10.1016/j.cpc.2008.01.036). URL: <https://doi.org/10.1016/j.cpc.2008.01.036>.
- [88] ATLAS Collaboration. *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model*. ATL-PHYS-PUB-2016-017. 2016. URL: <https://cds.cern.ch/record/2206965>.
- [89] R. D. Ball et al. ‘Parton distributions with LHC data’. In: *Nuclear Physics B* 867.2 (2013), pp. 244–289. ISSN: 0550-3213. DOI: <https://doi.org/10.1016/j.nuclphysb.2012.10.003>. URL: <https://www.sciencedirect.com/science/article/pii/S0550321312005500>.
- [90] D. J. Lange. ‘The EvtGen particle decay simulation package’. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 462.1 (2001). BEAUTY2000, Proceedings of the 7th Int. Conf. on B-Physics at Hadron Machines, pp. 152–155. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(01\)00089-4](https://doi.org/10.1016/S0168-9002(01)00089-4). URL: <https://www.sciencedirect.com/science/article/pii/S0168900201000894>.
- [91] E. Bothmann et al. ‘Event generation with Sherpa 2.2’. In: *SciPost Phys.* 7 (2019), p. 034. DOI: [10.21468/SciPostPhys.7.3.034](https://doi.org/10.21468/SciPostPhys.7.3.034). URL: <https://scipost.org/10.21468/SciPostPhys.7.3.034>.
- [92] ATLAS Collaboration. *Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector*. 2022. DOI: [10.48550/ARXIV.2209.10910](https://arxiv.org/abs/2209.10910). URL: <https://arxiv.org/abs/2209.10910>.
- [93] and G. Aad et al. ‘Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment’. In: *Journal of High Energy Physics* 2022.8 (Aug. 2022). DOI: [10.1007/jhep08\(2022\)089](https://doi.org/10.1007/jhep08(2022)089). URL: [https://doi.org/10.1007/jhep08\(2022\)089](https://doi.org/10.1007/jhep08(2022)089).

- [94] S. P. MARTIN. ‘A SUPERSYMMETRY PRIMER’. In: *Perspectives on Supersymmetry*. WORLD SCIENTIFIC, July 1998, pp. 1–98. DOI: [10.1142/9789812839657_0001](https://doi.org/10.1142/9789812839657_0001). URL: https://doi.org/10.1142/9789812839657_0001.
- [95] ATLAS Collaboration. *ATLAS Computing Acknowledgements*. ATL-SOFT-PUB-2021-003. URL: <https://cds.cern.ch/record/2776662>.
- [96] A. Djouadi and J. Quevillon. ‘The MSSM Higgs sector at a high MSUSY: reopening the low $\tan \beta$ regime and heavy Higgs searches’. In: *Journal of High Energy Physics* 2013.10 (Oct. 2013). DOI: [10.1007/jhep10\(2013\)028](https://doi.org/10.1007/jhep10(2013)028). URL: [https://doi.org/10.1007/jhep10\(2013\)028](https://doi.org/10.1007/jhep10(2013)028).
- [97] G. Branco et al. ‘Theory and phenomenology of two-Higgs-doublet models’. In: *Physics Reports* 516.1-2 (July 2012), pp. 1–102. DOI: [10.1016/j.physrep.2012.02.002](https://doi.org/10.1016/j.physrep.2012.02.002). URL: <https://doi.org/10.1016/j.physrep.2012.02.002>.
- [98] Y.-X. Liu. *Introduction to Extra Dimensions and Thick Braneworlds*. 2017. DOI: [10.48550/ARXIV.1707.08541](https://arxiv.org/abs/1707.08541). URL: <https://arxiv.org/abs/1707.08541>.
- [99] L. Randall and R. Sundrum. ‘Large Mass Hierarchy from a Small Extra Dimension’. In: *Physical Review Letters* 83.17 (Oct. 1999), pp. 3370–3373. DOI: [10.1103/physrevlett.83.3370](https://doi.org/10.1103/physrevlett.83.3370). URL: <https://doi.org/10.1103/physrevlett.83.3370>.
- [100] A. Carvalho. *Gravity particles from Warped Extra Dimensions, predictions for LHC*. 2014. DOI: [10.48550/ARXIV.1404.0102](https://arxiv.org/abs/1404.0102). URL: <https://arxiv.org/abs/1404.0102>.
- [101] I. Doršner et al. ‘Physics of leptoquarks in precision experiments and at particle colliders’. In: *Physics Reports* 641 (2016). Physics of leptoquarks in precision experiments and at particle colliders, pp. 1–68. ISSN: 0370-1573. DOI: <https://doi.org/10.1016/j.physrep.2016.06.001>. URL: <https://www.sciencedirect.com/science/article/pii/S0370157316301314>.
- [102] W. Buchmüller, R. Rückl and D. Wyler. ‘Leptoquarks in lepton-quark collisions’. In: *Physics Letters B* 191.4 (1987), pp. 442–448. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/0370-2693\(87\)90637-X](https://doi.org/10.1016/0370-2693(87)90637-X). URL: <https://www.sciencedirect.com/science/article/pii/037026938790637X>.

Auxiliary material

B Efficiency Histograms (Legacy)

L1

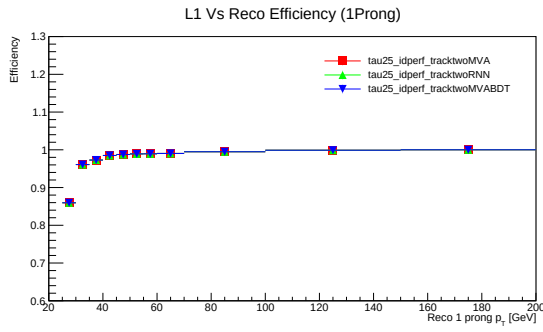


Figure 83: Reco 1P Pt v/s Efficiency. *idperf* chains.

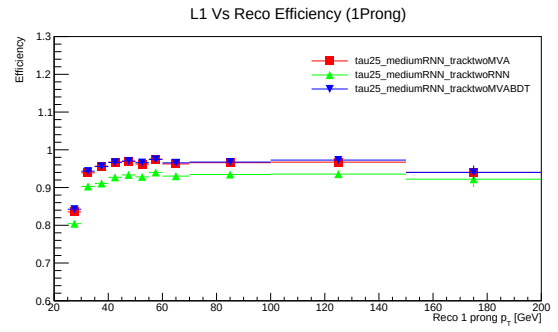


Figure 84: Reco 1P Pt v/s Efficiency. *mediumRNN* chains

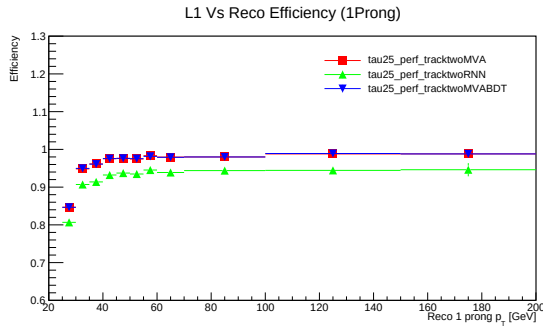


Figure 85: Reco 1P Pt v/s Efficiency. *perf* chains

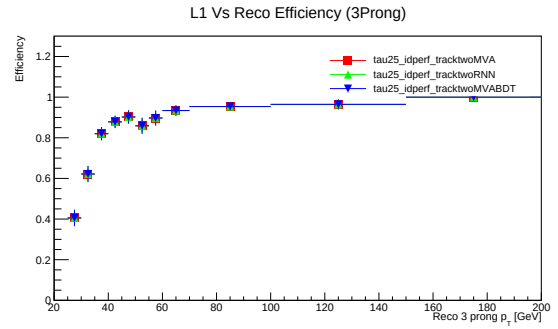


Figure 86: Reco 3P Pt v/s Efficiency. *idperf* chains.

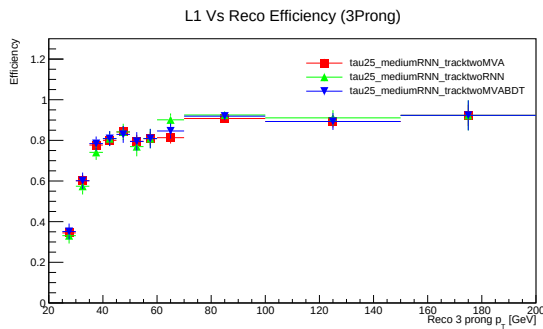


Figure 87: Reco 3P Pt v/s Efficiency. *mediumRNN* chains.

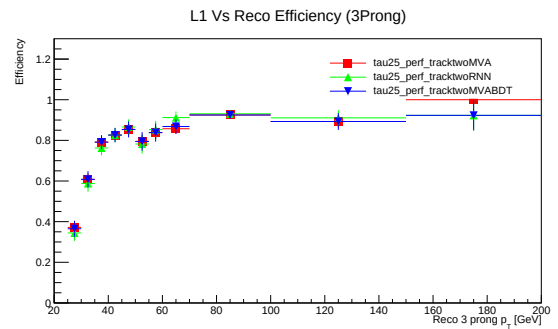


Figure 88: Reco 3P Pt v/s Efficiency

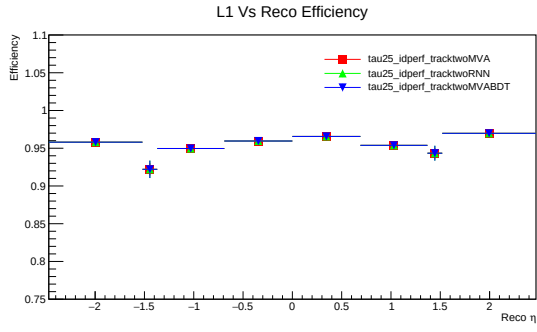


Figure 89: ν v/s Efficiency. *idperf* chains.

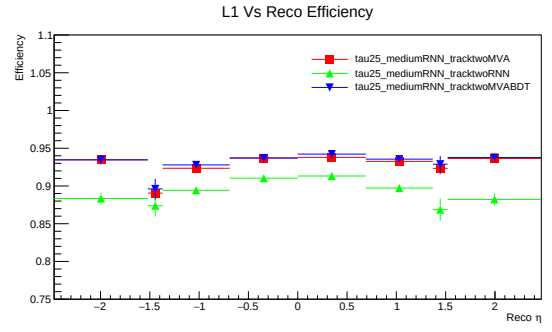


Figure 90: ν v/s Efficiency. *mediumRNN* chains.

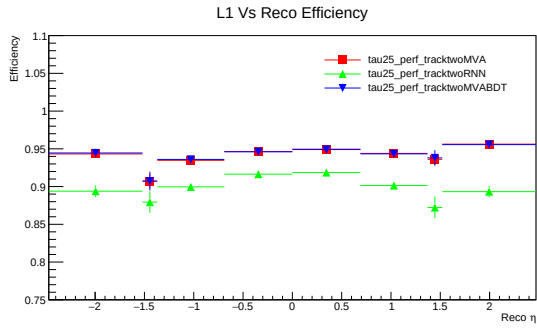


Figure 91: ν v/s Efficiency. *perf* chains.

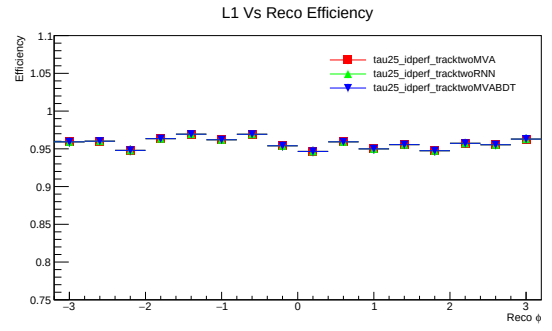


Figure 92: Reco ϕ v/s Efficiency. *idperf* chains.

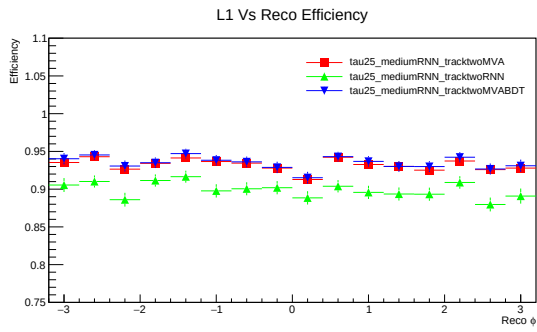


Figure 93: Reco ϕ v/s Efficiency. *mediumRNN* chains

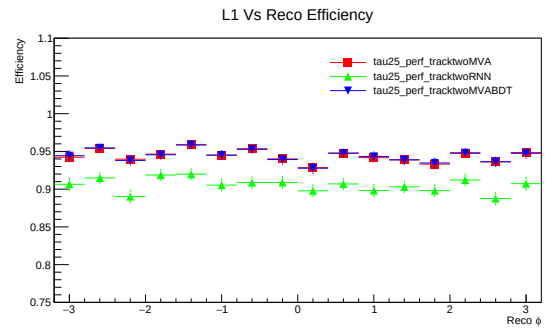


Figure 94: Reco ϕ v/s Efficiency. *perf* chains

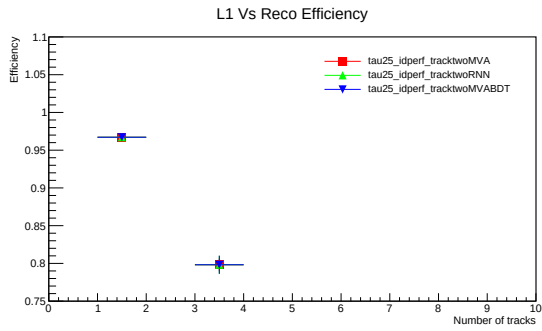


Figure 95: Number of tracks v/s Nevents. *idperf* chains.

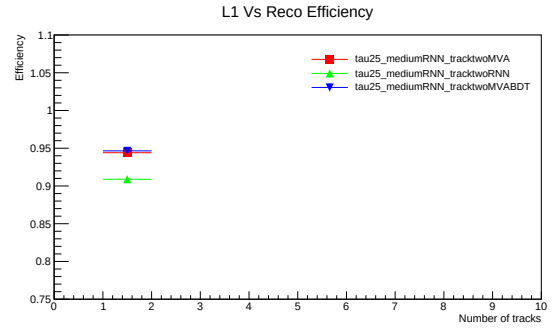


Figure 96: Number of tracks v/s Nevents. *mediumRNN* chains.

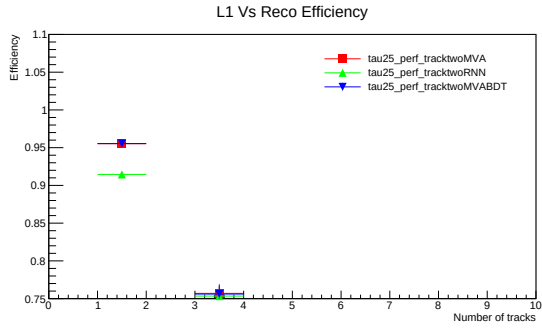


Figure 97: Number of tracks v/s Nevents. *perf* chains.

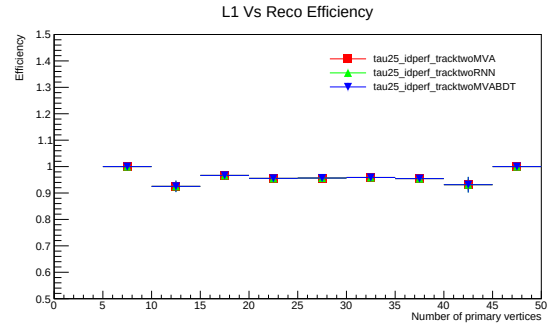


Figure 98: Number of the primary vertices v/s Efficiency. *idperf* chains.

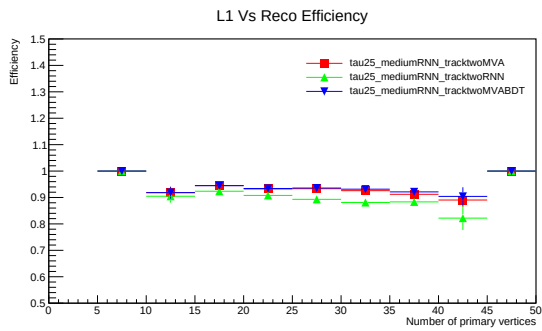


Figure 99: Number of the primary vertices v/s Efficiency. *mediumRNN* chains.

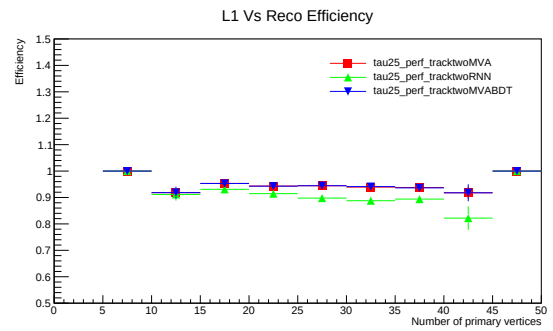


Figure 100: Number of the primary vertices v/s Efficiency. *perf* chains.

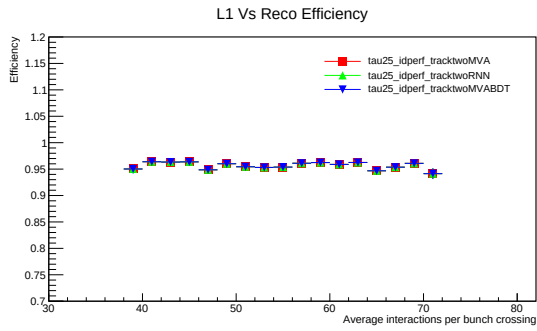


Figure 101: Average interactions per bunch crossing vs Efficiency. *idperf* chains.

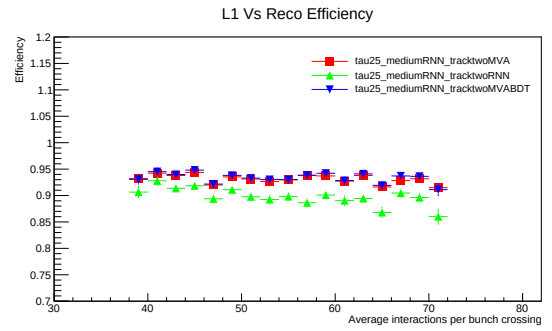


Figure 102: Average interactions per bunch crossing vs Efficiency. *mediumRNN* chains.

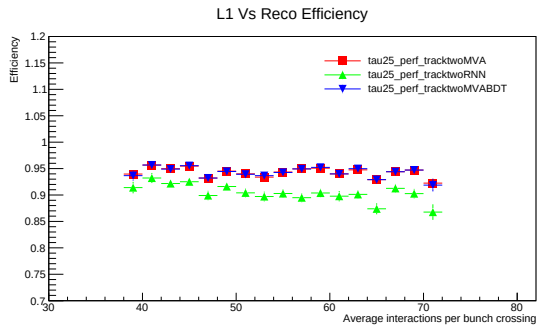


Figure 103: Average interactions per bunch crossing vs Efficiency. *perf* chains.

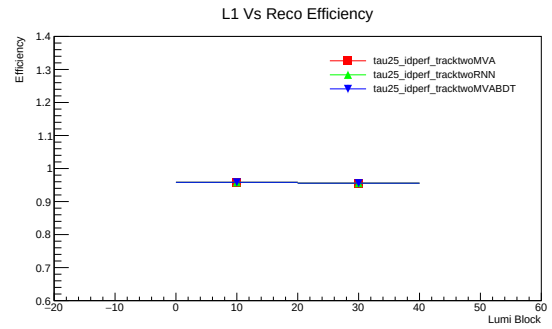


Figure 104: Lumi Block v/s Efficiency. *idperf* chains

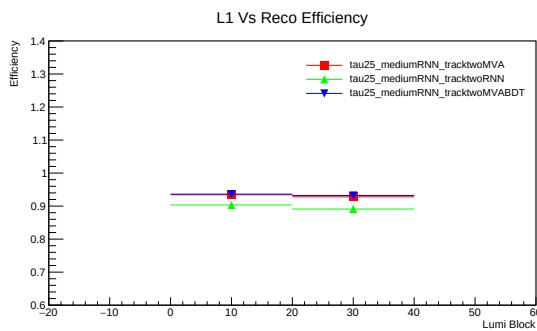


Figure 105: Lumi Block v/s Efficiency. *mediumRNN* chains

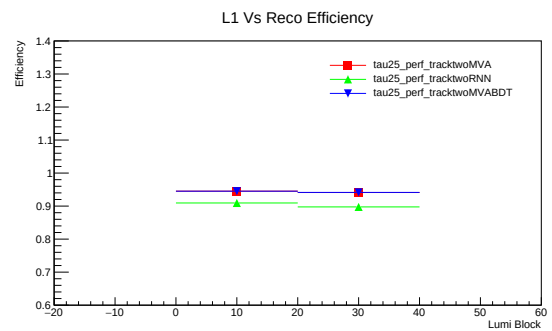


Figure 106: Lumi Block v/s Efficiency. *perf* chains.

HLT

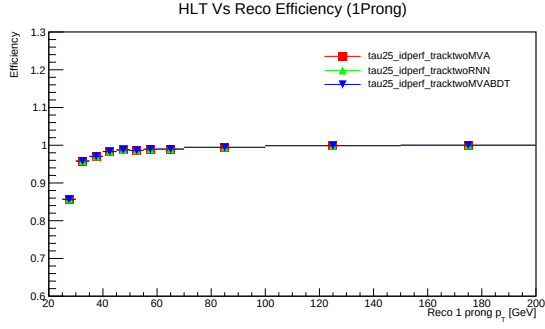


Figure 107: Reco 1P Pt v/s Efficiency. *idperf* chains.

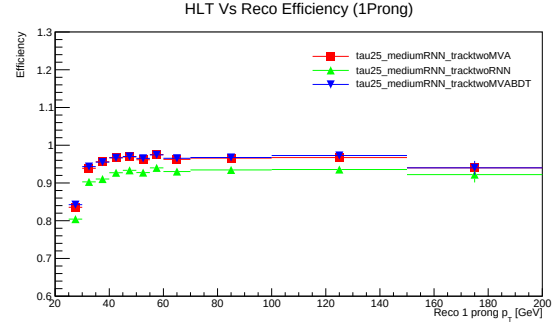


Figure 108: Reco 1P Pt v/s Efficiency. *mediumRNN* chains.

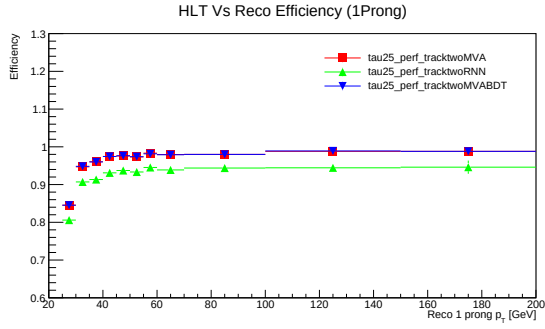


Figure 109: Reco 1P Pt v/s Efficiency. *perf* chains.

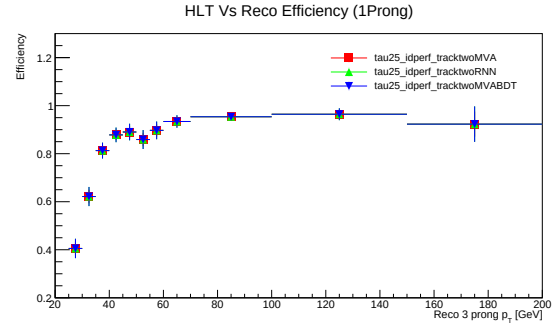


Figure 110: Reco 3P Pt v/s Efficiency. *idperf* chains.

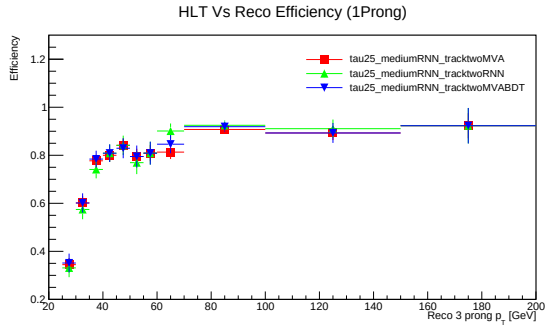


Figure 111: Reco 3P Pt v/s Efficiency. *mediumRNN* chains.

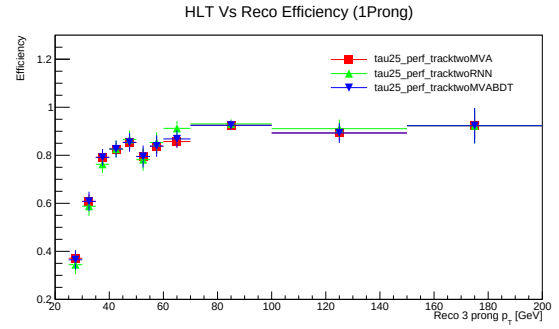


Figure 112: Reco 3P Pt v/s Efficiency. *perf* chains.

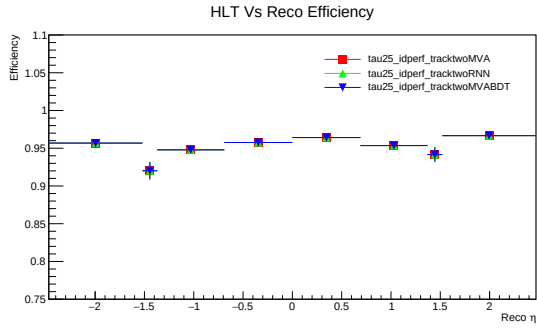


Figure 113: Reco ν v/s Efficiency. *idperf* chains.

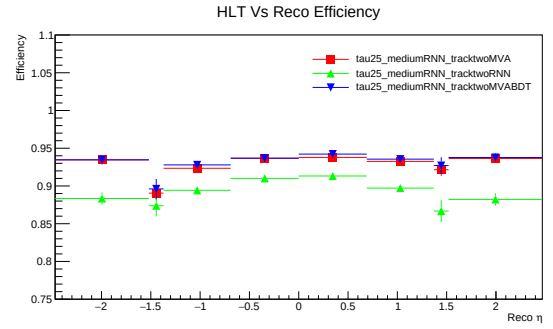


Figure 114: Reco ν v/s Efficiency. *mediumRNN* chains.

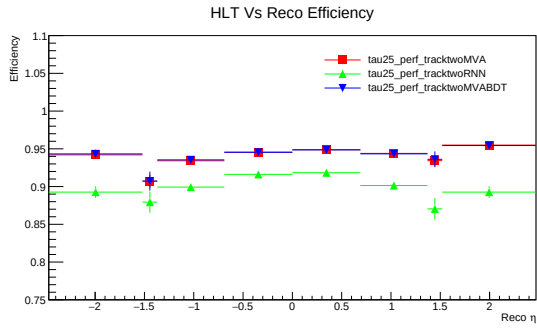


Figure 115: Reco ν v/s Efficiency. *perf* chains.

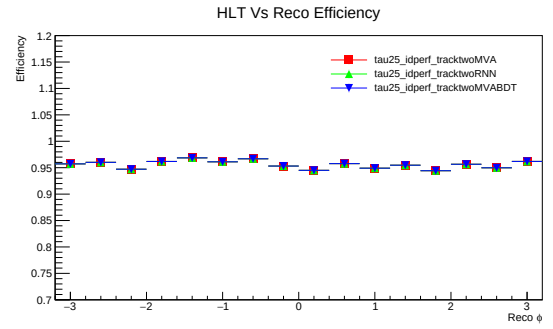


Figure 116: Reco ϕ v/s Efficiency. *idperf* chains.

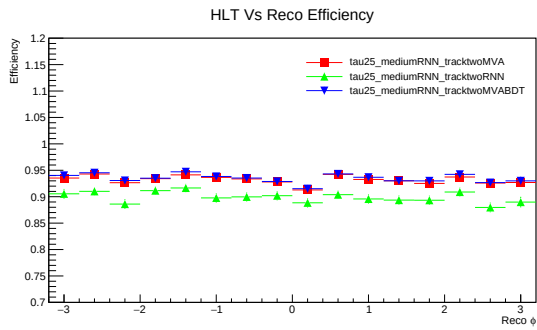


Figure 117: Reco ϕ v/s Efficiency. *mediumRNN* chains.

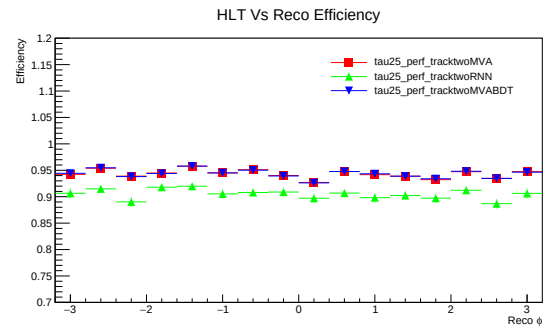


Figure 118: Reco ϕ v/s Efficiency. *perf* chains.

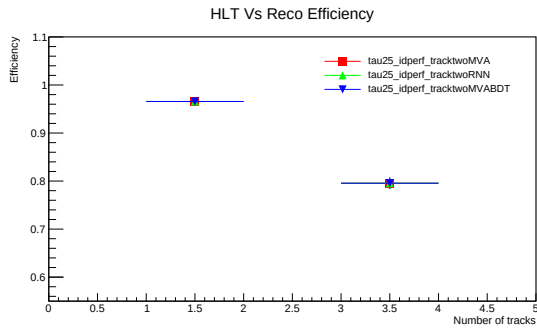


Figure 119: Number of Tracks v/s Efficiency. *idperf* chains.

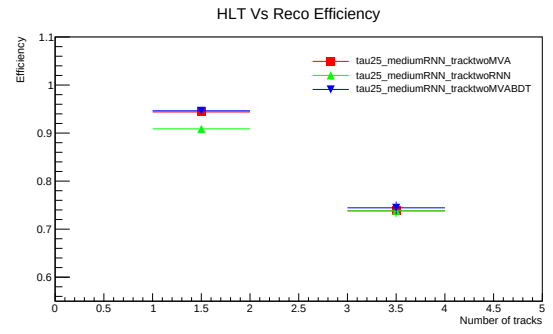


Figure 120: Number of the Tracks v/s Efficiency. *medium-RNN* chains.

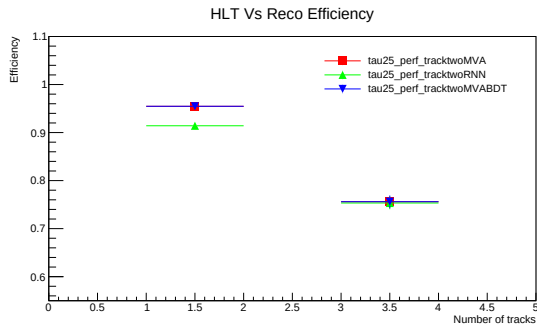


Figure 121: Number of the Tracks v/s Efficiency. *perf* chains.

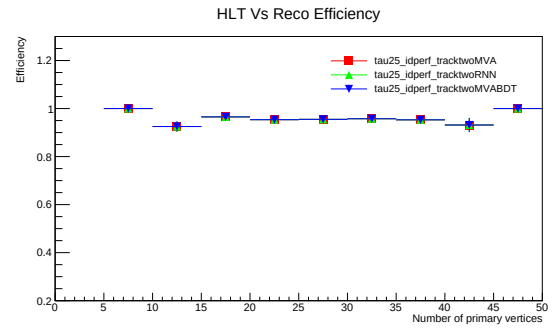


Figure 122: Number of the primary vertices v/s Efficiency. *idperf* chains.

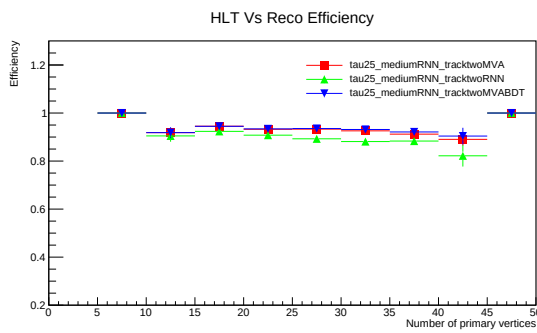


Figure 123: Number of the primary vertices v/s Efficiency. *mediumRNN* chains.

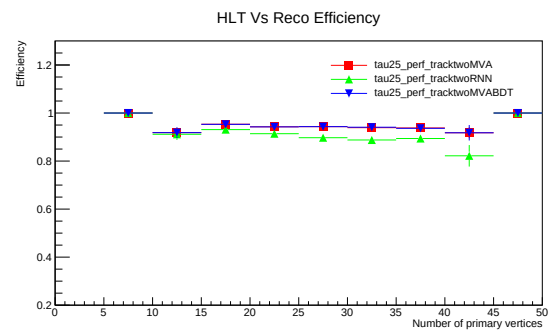


Figure 124: Number of the primary vertices v/s Efficiency. *perf* chains.

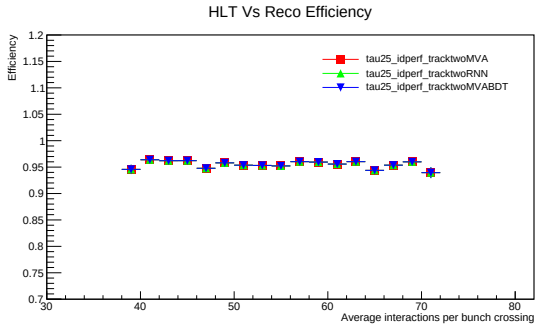


Figure 125: Average interactions per bunch crossing v/s Efficiency. *idperf* chains.

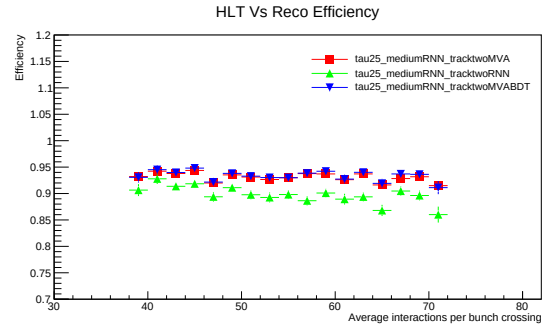


Figure 126: Average interactions per bunch crossing v/s Efficiency. *mediumRNN* chains.

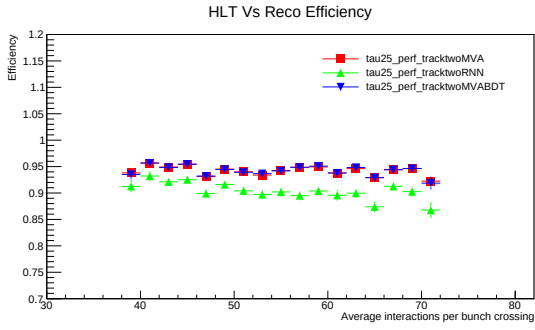


Figure 127: Average interactions per bunch crossing v/s Efficiency. *perf* chains.

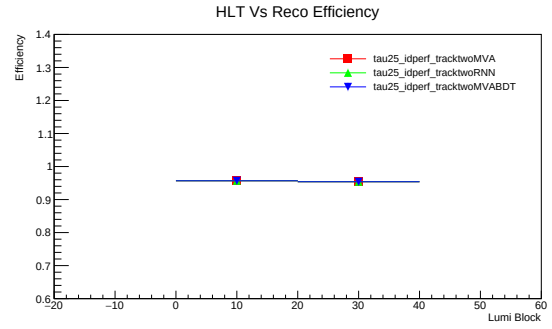


Figure 128: Lumi Block v/s Efficiency. *idperf* chains.

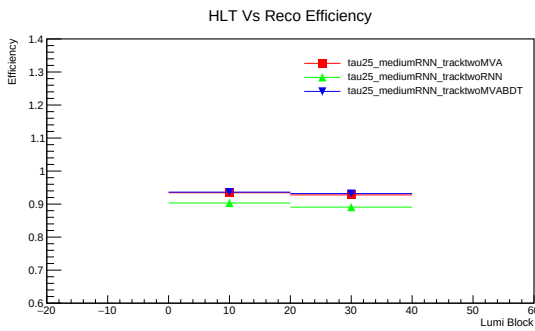


Figure 129: Lumi Block v/s Efficiency. *mediumRNN* chains.

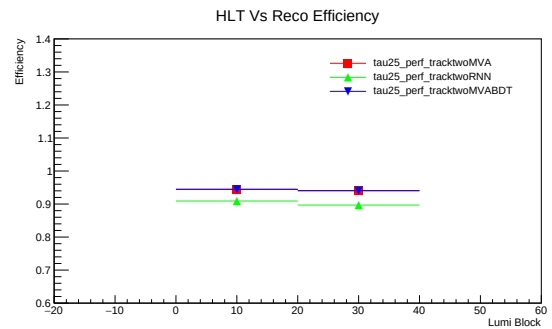


Figure 130: Lumi Block v/s Efficiency. *perf* chains.

C Visible Variables Histograms

Visible Variables Histograms⁶.

C.1 EFVsTruth

> Single Variables <

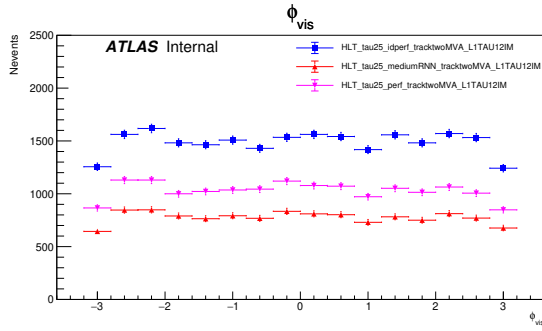


Figure 131: ϕ_{vis} v/s Nevents.

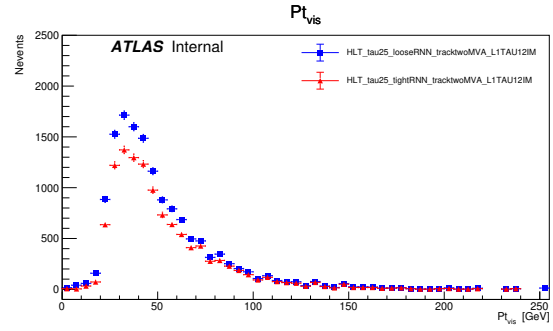


Figure 132: Pt_{vis} v/s Nevents.

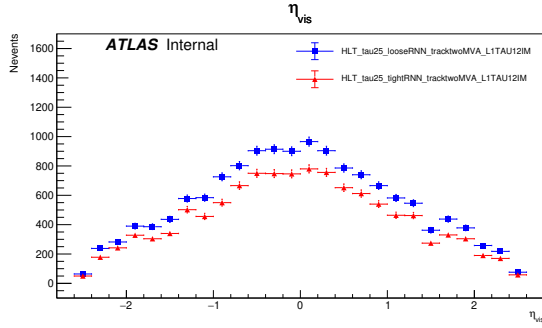


Figure 133: η_{vis} v/s Nevents.

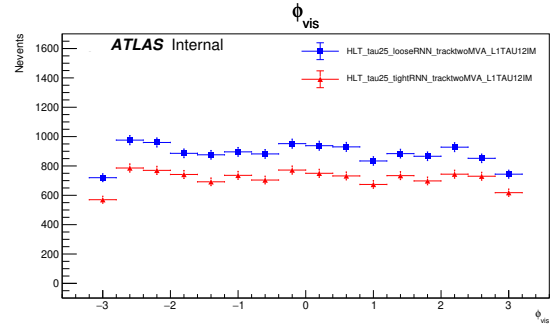


Figure 134: ϕ_{vis} v/s Nevents.

⁶ ttbar Sample 19th in Table 2

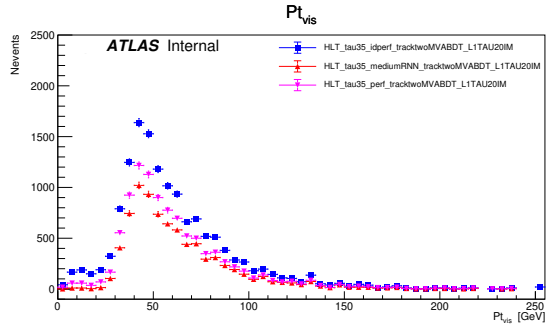


Figure 135: $P_{t_{vis}}$ v/s Nevents.

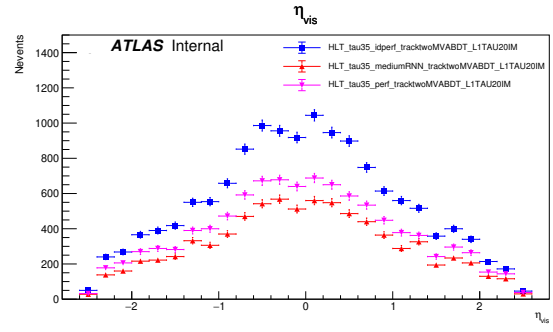


Figure 136: η_{vis} v/s Nevents.

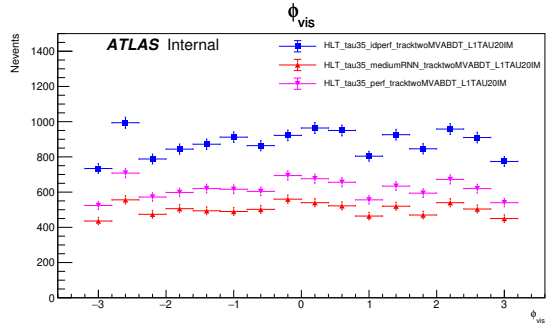


Figure 137: ϕ_{vis} v/s Nevents.

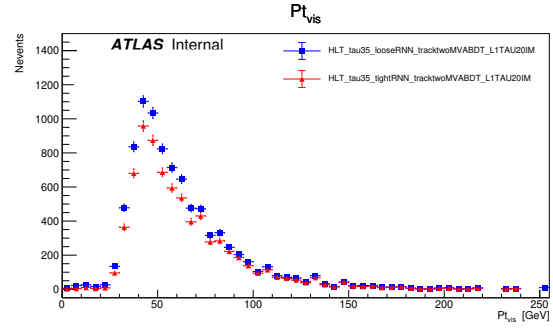


Figure 138: $P_{t_{vis}}$ v/s Nevents.

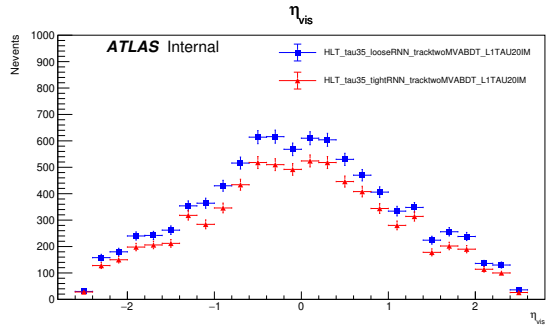


Figure 139: η_{vis} v/s Nevents.

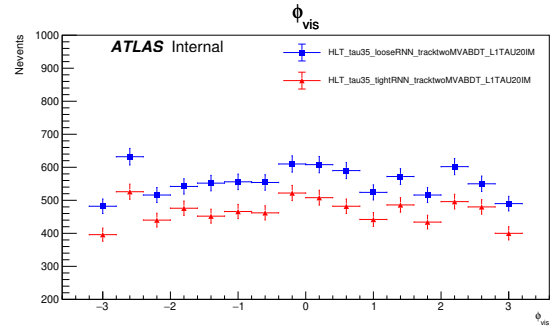


Figure 140: ϕ_{vis} v/s Nevents.

Profile Histograms
 $> (\text{reco variable} - \text{truth variable})/\text{truth variable vs variable} <$

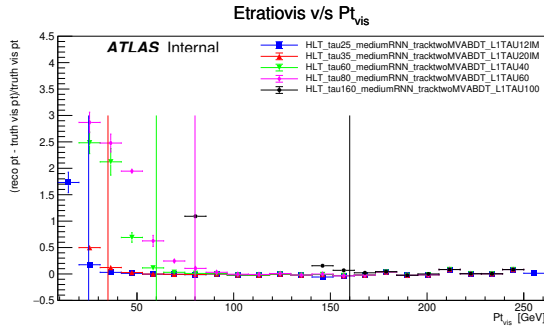


Figure 141: Pt_{vis} v/s Etratiovis.

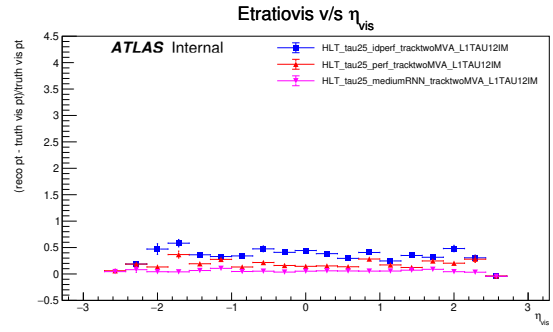


Figure 142: Pt_{vis} v/s Etratiovis.

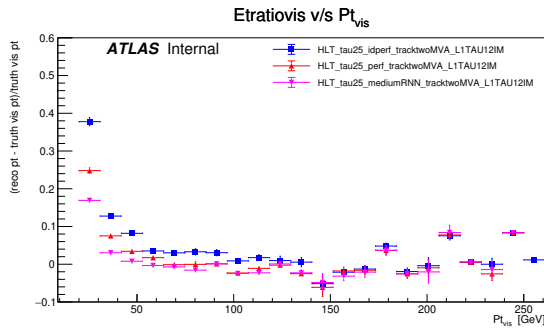


Figure 143: Pt_{vis} v/s Etratiovis.

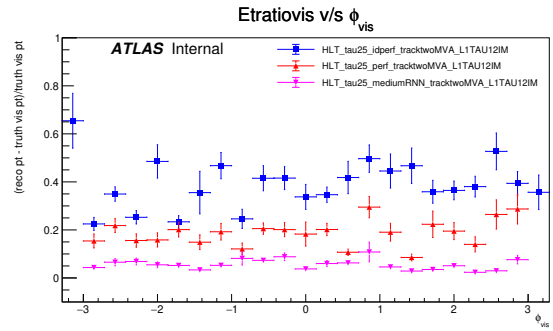


Figure 144: ϕ_{vis} v/s Etratiovis.

C.2 Truth Efficiency

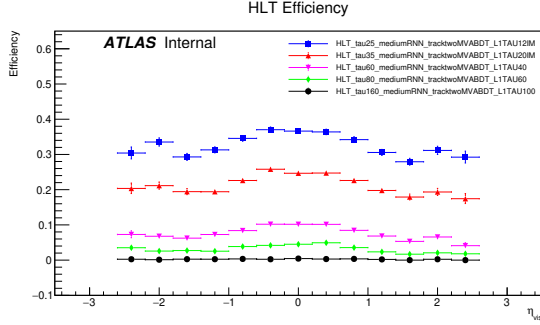


Figure 145: η_{vis} v/s Efficiency.

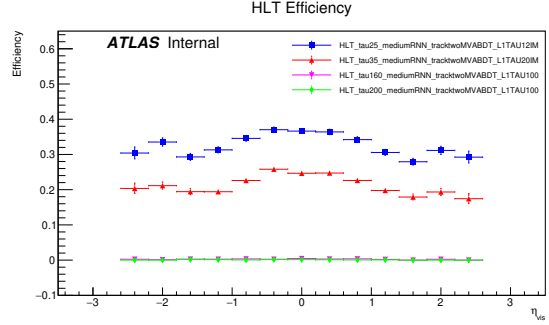


Figure 146: η_{vis} v/s Efficiency.

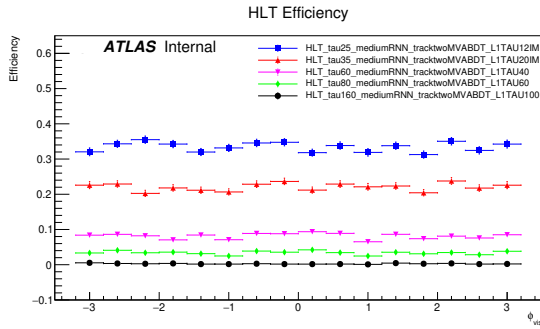


Figure 147: ϕ_{vis} v/s Efficiency.

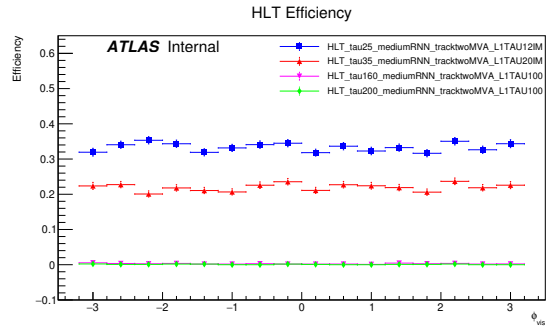


Figure 148: ϕ_{vis} v/s Efficiency.

D DiTau Histograms

Histograms Di Tau triggers with a $t\bar{t}$ sample (table 2 - 19th) .

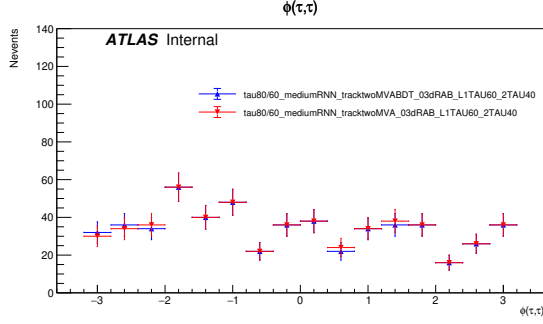


Figure 149: $\phi(\tau, \tau)$ v/s Nevents.

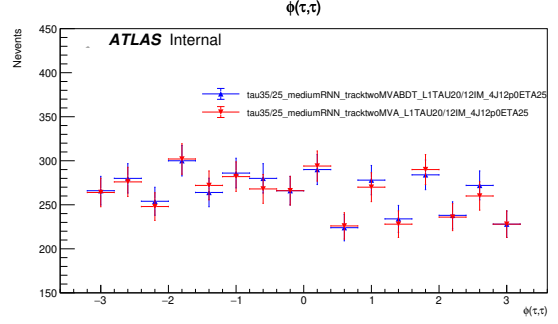


Figure 150: $\phi(\tau, \tau)$ v/s Nevents.

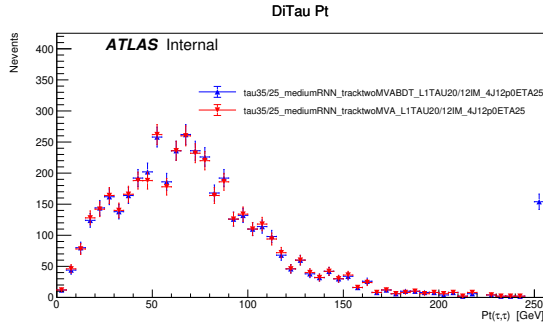


Figure 151: $Pt(\tau, \tau)$ v/s Nevents.

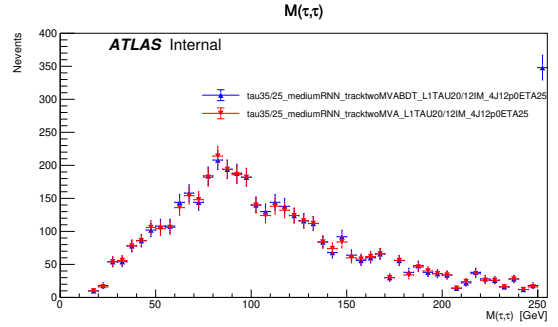


Figure 152: $M(\tau, \tau)$ v/s Nevents.

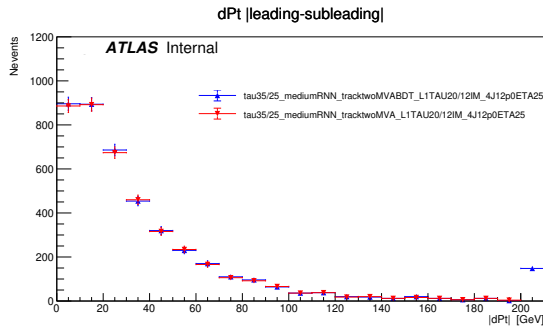


Figure 153: $|dPt|$ v/s Nevents.

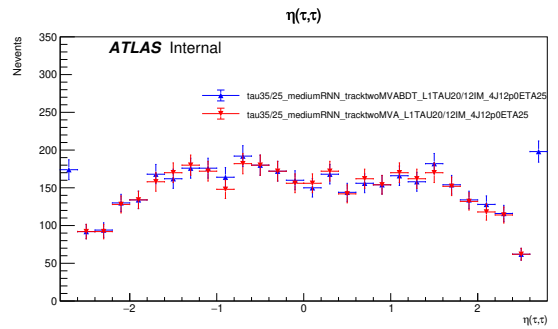


Figure 154: $\eta(\tau, \tau)$ v/s Nevents.

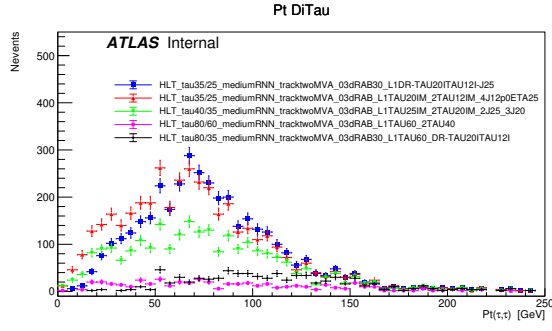


Figure 155: $Pt(\tau, \tau)$ v/s Nevents.

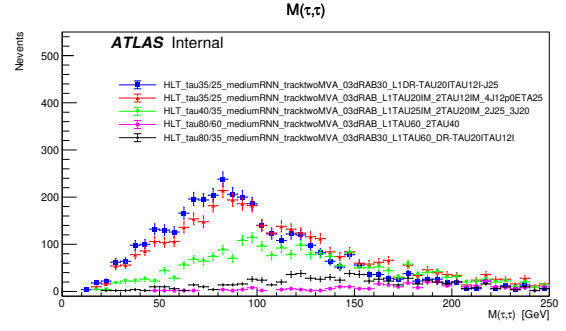


Figure 156: $M(\tau, \tau)$ v/s Nevents.

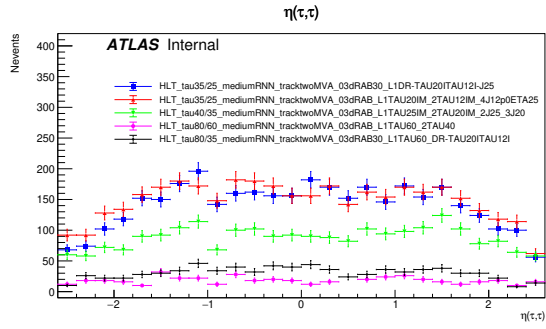


Figure 157: $\eta(\tau, \tau)$ v/s Nevents.

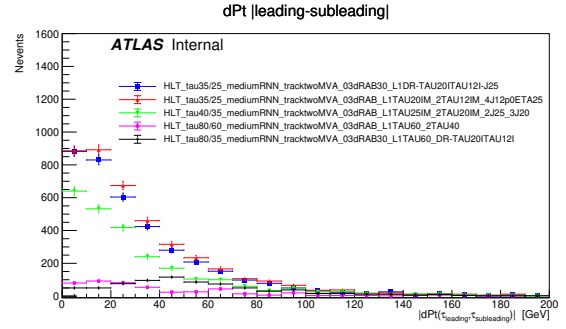


Figure 158: $|dPt(\tau, \tau)|$ v/s Nevents.

E χ^2 Square Test

These are histograms with slightly lower test p-values.

Physics_Main_Run431885+Physics
Run440543/HLT_Efficiency
HLT_tau25_idperf_tracktwoMVA_L1TAU12IM
1P-3P

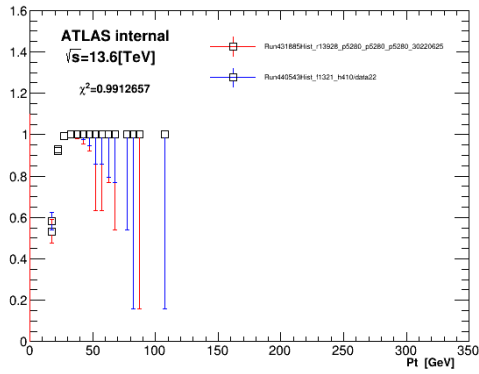


Figure 159: Pt v/s Efficiency.
1P

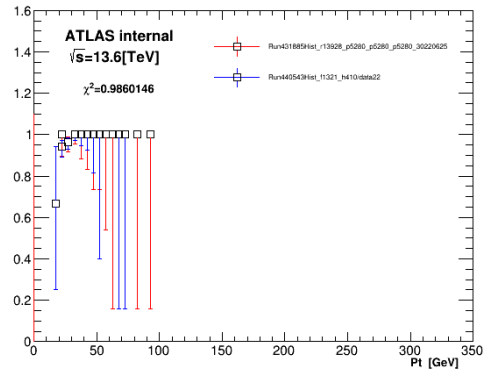


Figure 160: Pt v/s Nevents.
3P

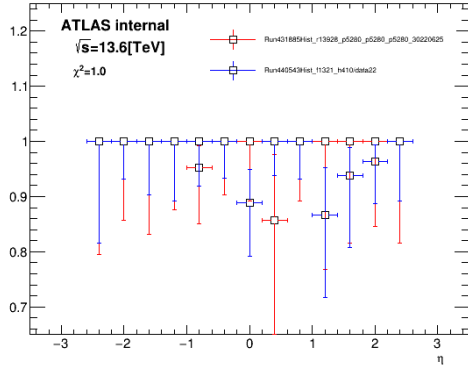


Figure 161: η v/s Efficiency.
3P

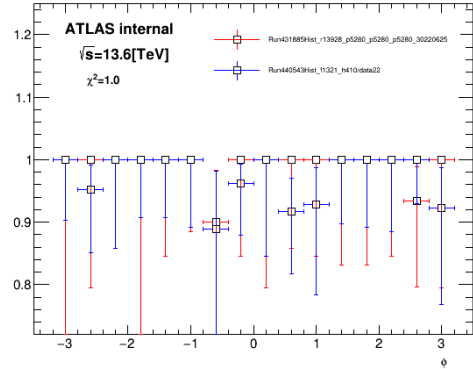


Figure 162: ϕ v/s Efficiency.
3P

Physics_Main_Run431885+Physics
Run440543/HLT_Efficiency
HLT_tau25_mediumRNN_tracktwoMVA_L1TAU12IM
1P-3P

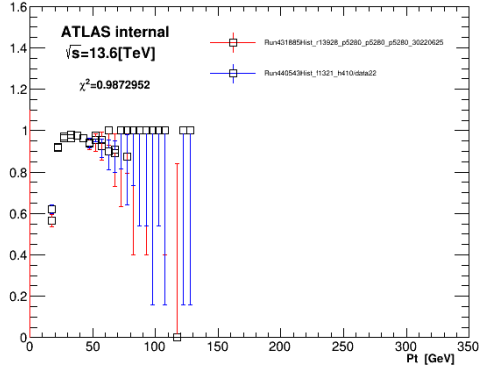


Figure 163: Pt v/s Efficiency.
1P

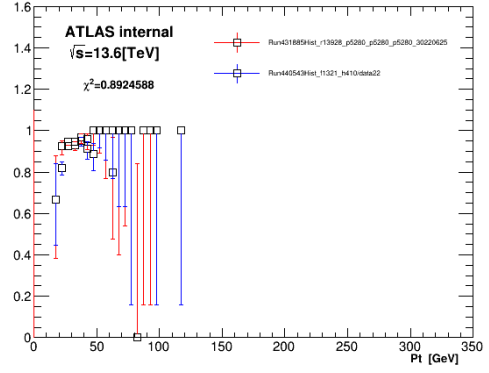


Figure 164: Pt v/s Nevents.
3P

F Non-resonant $b\bar{b}\tau_{lep}\tau_{had}$ CxAOD Histograms

F.1 Single Lepton Trigger (SLT)

Pre-fit input variable distributions in the di-Higgs $b\bar{b}\tau_{lep}\tau_{had}$ SLT.

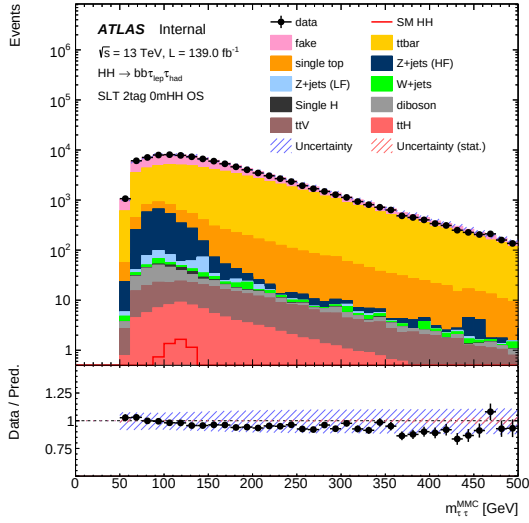


Figure 165: $m_{\tau\tau}^{MMC}$ v/s Events.
Baseline samples

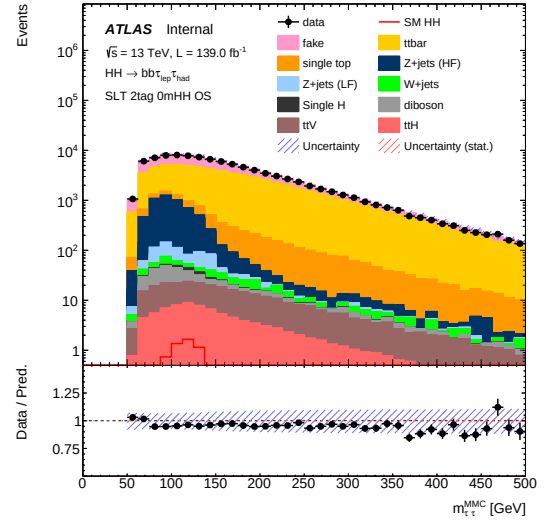


Figure 166: $m_{\tau\tau}^{MMC}$ v/s Events.
New Sherpa samples

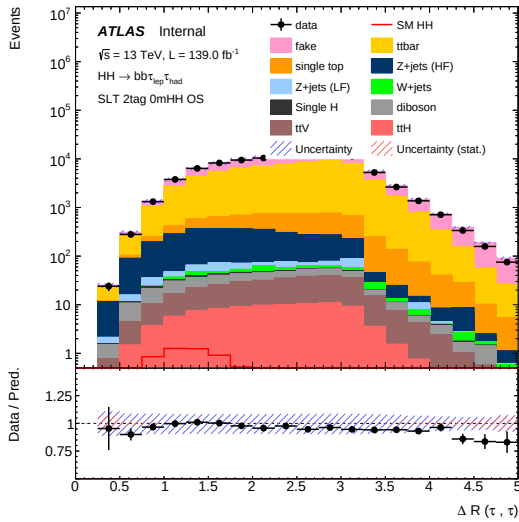


Figure 167: $\Delta R(\tau, \tau)$ v/s Events.
Baseline samples

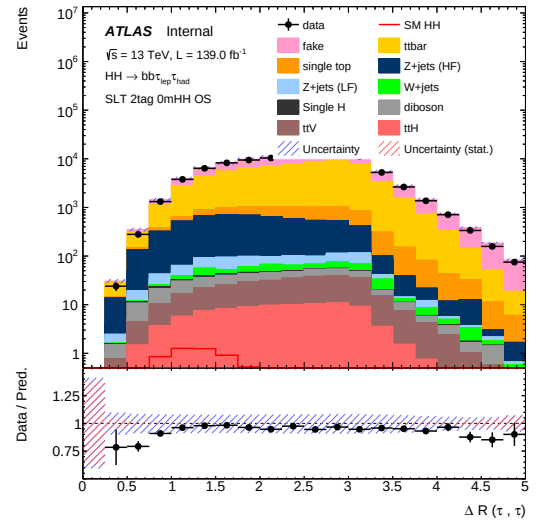


Figure 168: $\Delta R(\tau, \tau)$ v/s Events.
New Sherpa samples

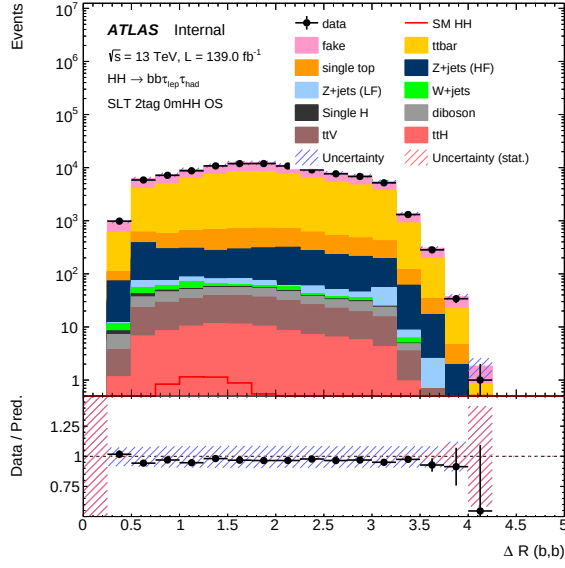


Figure 169: $\Delta R(b, b)$ v/s Events.
Baseline samples

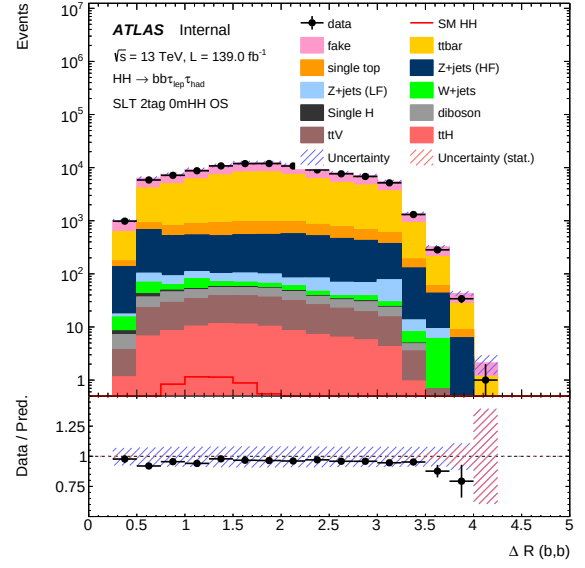


Figure 170: $\Delta R(b, b)$ v/s Events.
New Sherpa samples

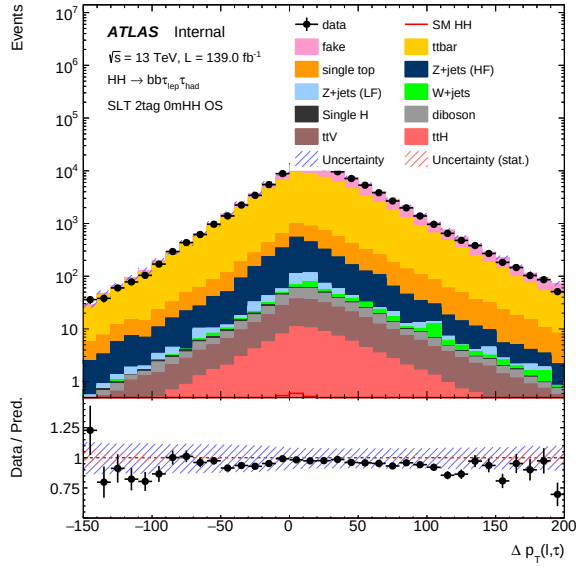


Figure 171: $\Delta P_t(l, \tau)$ v/s Events.
Baseline samples

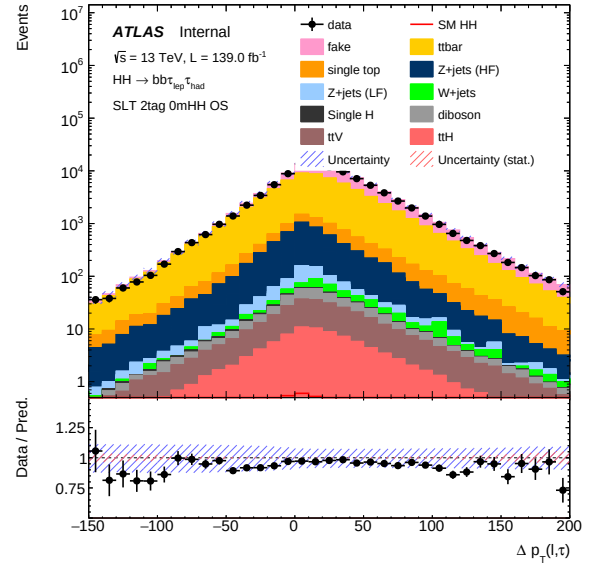


Figure 172: $\Delta P_t(l, \tau)$ v/s Events.
New Sherpa samples

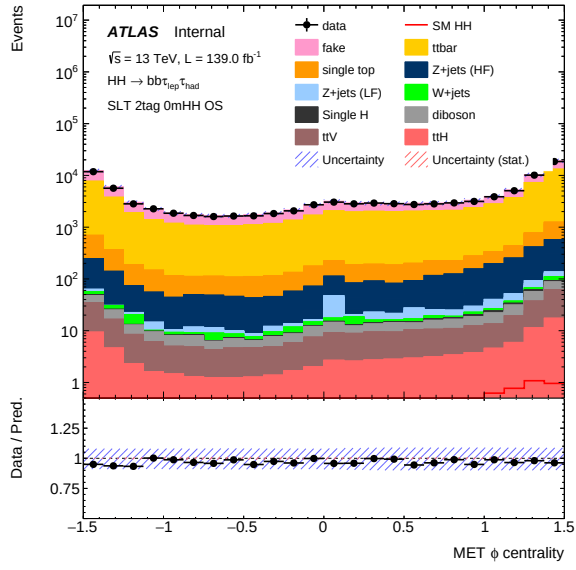


Figure 173: MET ϕ centrality v/s Events.
Baseline samples

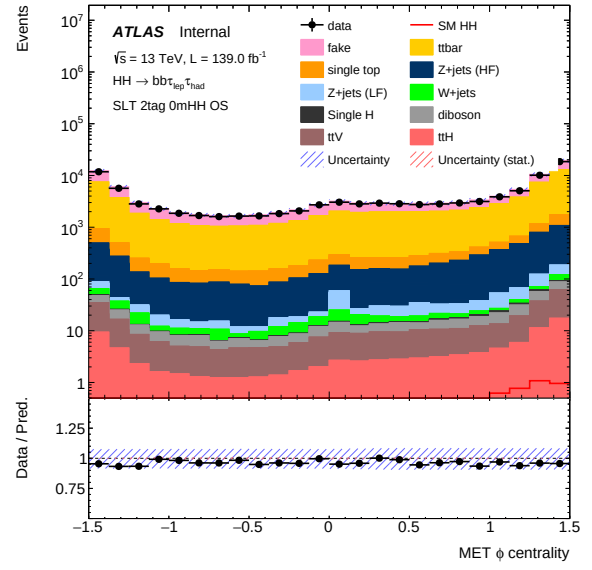


Figure 174: MET ϕ centrality v/s Events.
New Sherpa samples

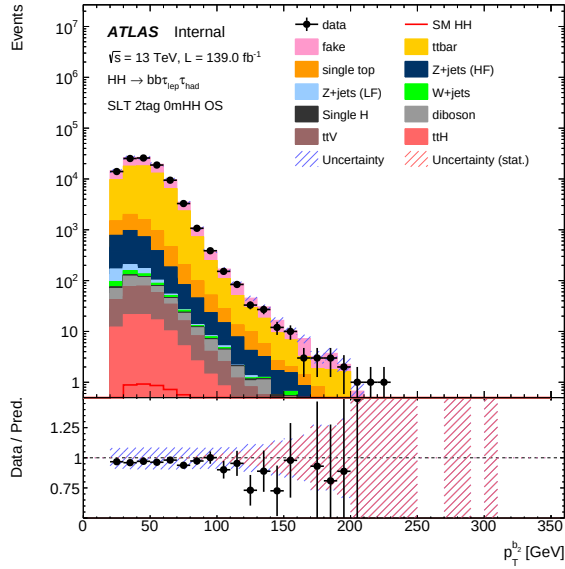


Figure 175: $p_T^{b_2}$ v/s Events.
Baseline samples

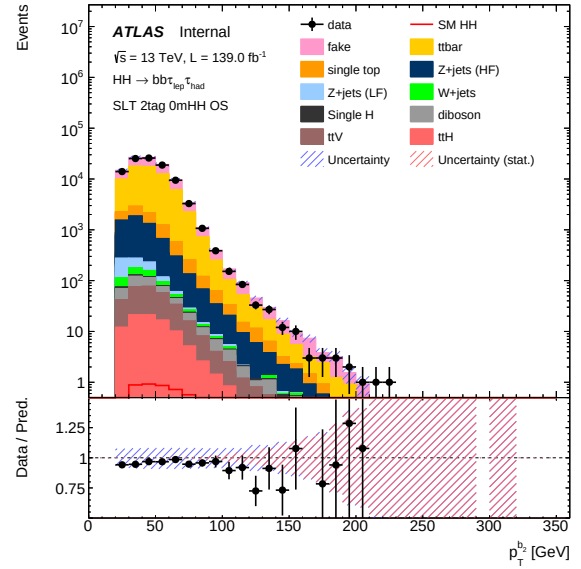


Figure 176: $p_T^{b_2}$ v/s Events.
New Sherpa samples

F.2 Lepton Tau Trigger (LTT)

Pre-fit input variable distributions in the di-Higgs $b\bar{b}\tau_{lep}\tau_{had}$ LTT.

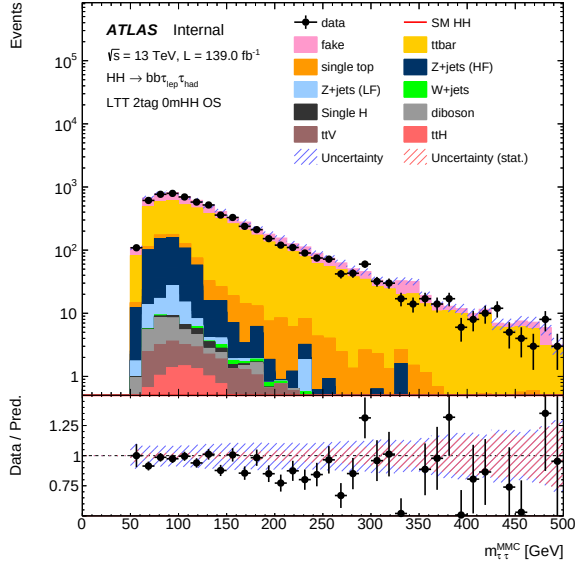


Figure 177: $m_{\tau\tau}^{MMC}$ v/s Events.
Baseline samples

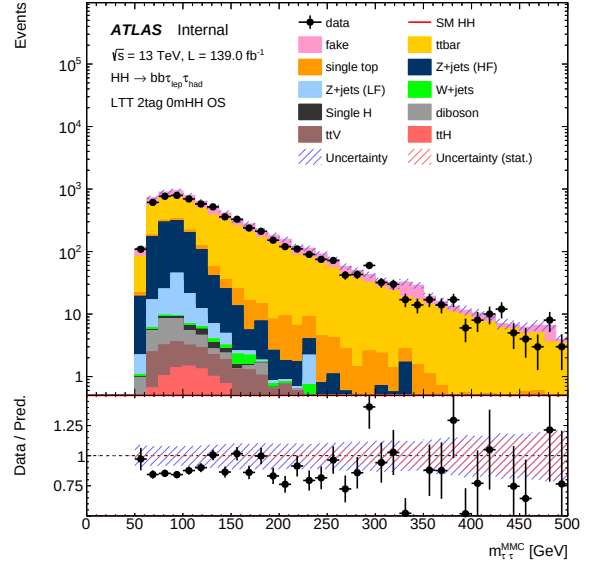


Figure 178: $m_{\tau\tau}^{MMC}$ v/s Events.
New Sherpa samples

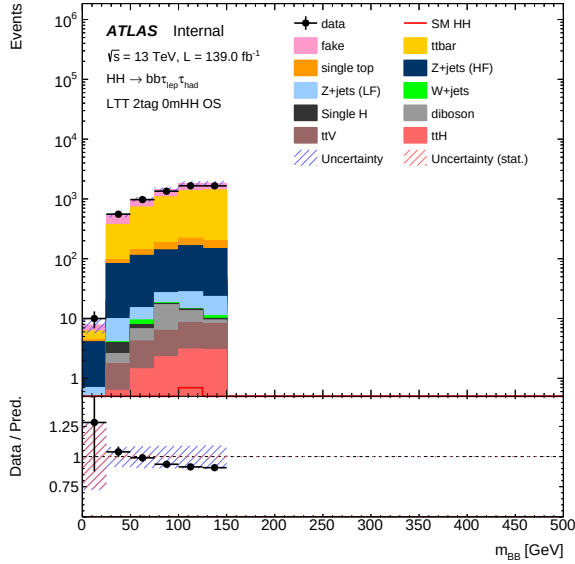


Figure 179: m_{bb} v/s Events.
Baseline samples

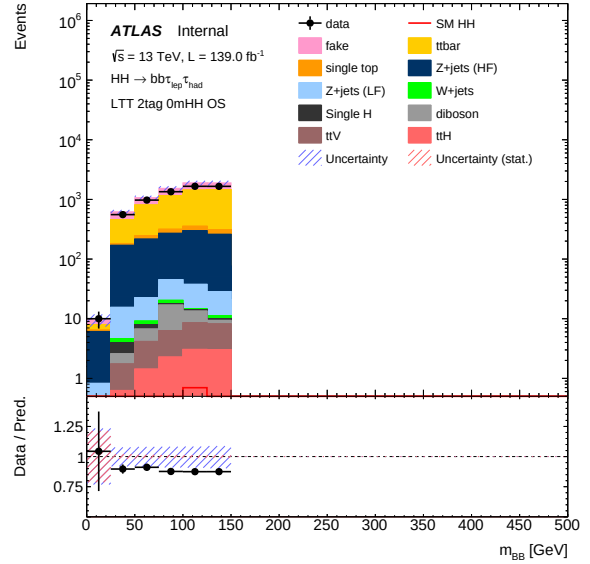


Figure 180: m_{bb} v/s Events.
New Sherpa samples

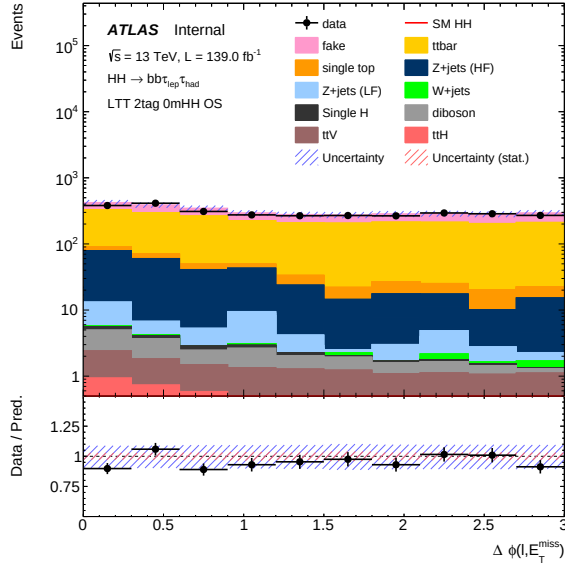


Figure 181: $\Delta\phi(l, E_T^{miss})$ v/s Events.
 Baseline samples

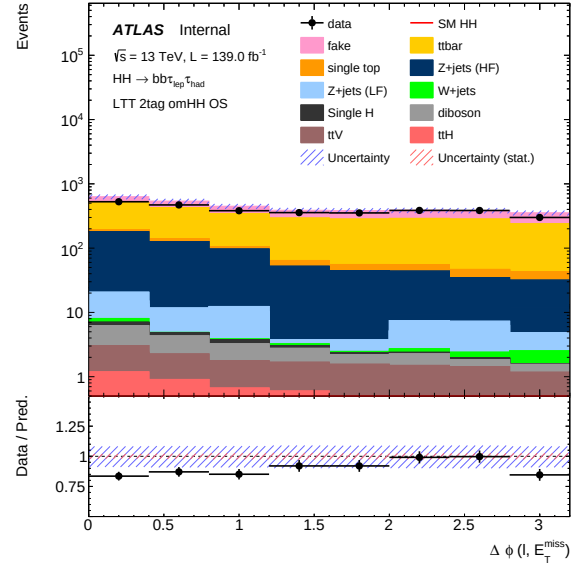


Figure 182: $\Delta\phi(l, E_T^{miss})$ v/s Events.
 New Sherpa samples

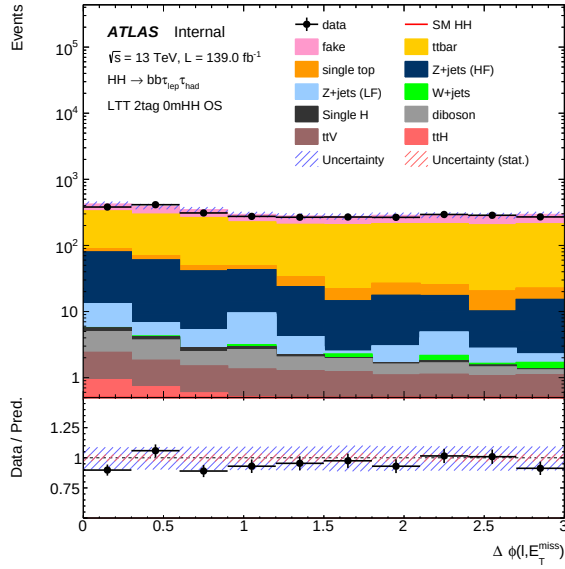


Figure 183: $\Delta\phi(l, E_T^{miss})$ v/s Events.
 Baseline samples

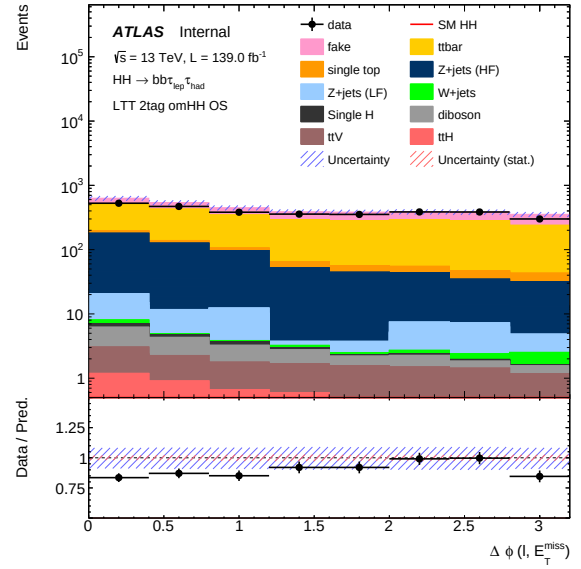


Figure 184: $\Delta\phi(l, E_T^{miss})$ v/s Events.
 New Sherpa samples

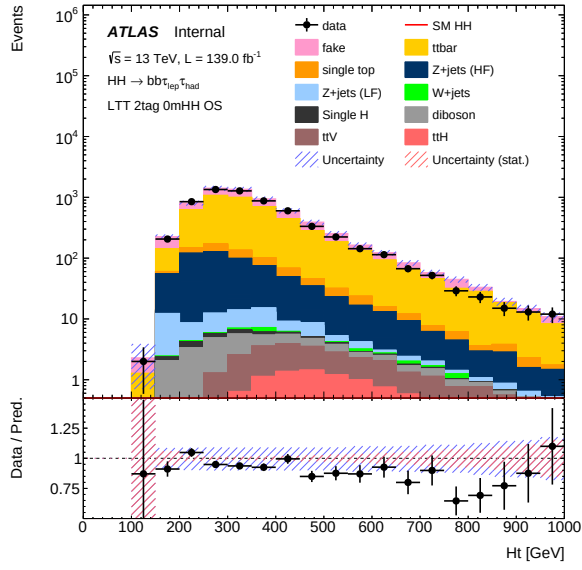


Figure 185: Ht v/s Events.
Baseline samples

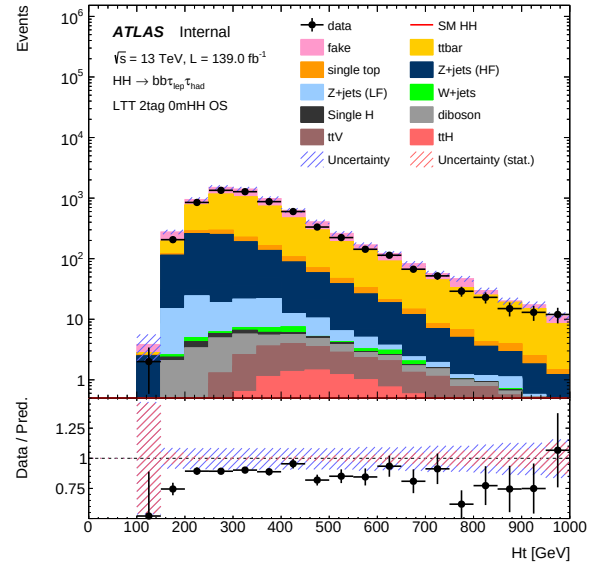


Figure 186: Ht v/s Events.
New Sherpa samples

G HepData material

G.1 Samples legacy & master trigger tau code

The table illustrates which samples are used in the context of the τ trigger monitoring code.

Dataset List		
Release 21.3 (legacy)	valid1.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_nonallhad.recon.AOD.e4993_s3214_d1536_d1537_r11578_tid18889280_00	13th
Master (AthenaMT)	valid1.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_nonallhad.recon.AOD.e4993_s3214_d1727_r13198_tid27345446_00	17th
	valid1.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_nonallhad.recon.AOD.e4993_s3214_d1732_r13252_tid27512968_00	18th
	valid1.410000.PowhegPythiaEvtGen_P2012_ttbar_hdamp172p5_nonallhad.recon.AOD.e4993_s3214_d1738_r13391_tid28072316_00	19th

Table 2: Dataset used for testing the histograms.

G.2 Signal & background samples for Higgs pair production in the $b\bar{b}\tau\tau$ channel.

Table 3: The generators used to simulate the signal and background processes. The acronyms ME, PS and UE are used for matrix element, parton shower and underlying event, respectively. Details of the simulation of the signal and background samples are described in text.

Process	ME generator	ME QCD order	ME PDF	PS and hadronisation	UE model tune	Cross section order
Signal						
non-resonant $gg \rightarrow HH$ (ggF)	POWHEGBOX v2	NLO	PDF4LHC15 NLO	PYTHIA 8.244	A14	NNLO FTApprox
non-resonant $qq \rightarrow qqHH$ (VBF)	MADGRAPH5-AMC@NLO 2.7.3	LO	NNPDF3.0 NLO	PYTHIA 8.244	A14	N3LO(QCD)
resonant $gg \rightarrow X \rightarrow HH$	MADGRAPH5-AMC@NLO 2.6.1	LO	NNPDF2.3 LO	HERWIG 7.1.3	H7.1-Default	-
Top-quark						
$t\bar{t}$	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.230	A14	NNLO+NNLL
t-channel	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.230	A14	NLO
s-channel	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.230	A14	NLO
Wt	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.230	A14	NLO
$t\bar{t}Z$	SHERPA 2.2.1	NLO	NNPDF3.0 NLO	SHERPA 2.2.1	Default	NLO
$t\bar{t}W$	SHERPA 2.2.8	NLO	NNPDF3.0 NLO	SHERPA 2.2.8	Default	NLO
Vector boson + jets						
W/Z + jets	SHERPA 2.2.1	NLO (≤ 2 jets) LO(3,4 jets)	NNPDF3.0 $NNLO$	SHERPA 2.2.1	Default	NNLO
Diboson						
WW,WZ,ZZ	SHERPA 2.2.1	NLO (≤ 1 jets) LO(2,3 jets)	NNPDF3.0 $NNLO$	SHERPA 2.2.1	Default	NLO
Single Higgs boson						
ggF	POWHEG BOX v2	NNLO	NNPDF3.0 NLO	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW)
VBF	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW)
$qq \rightarrow WH$	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW)
$qq \rightarrow ZH$	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.212	AZNLO	N3LO(QCD)+NLO(EW)
$gg \rightarrow ZH$	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.212	AZNLO	NLO+NNLL
$t\bar{t}H$	POWHEG BOX v2	NLO	NNPDF3.0 NLO	PYTHIA 8.230	A14	NLO

G.3 Trigger Menu 2021

The table represent all the tau trigger menu according to this qualification task⁷.

Tau Trigger Menu	
Description	Name
Primaries	HLT_tau160_mediumRNN_tracktwoMVABDT.L1TAU100 HLT_tau200_mediumRNN_tracktwoMVABDT.L1TAU100 HLT_tau160_mediumRNN_tracktwoMVABDT.L1eTAU140 HLT_tau200_mediumRNN_tracktwoMVABDT.L1eTAU140
Displaced Tau (ATR-21754)	HLT_tau180_mediumRNN_tracktwoLLP.L1TAU100 HLT_tau200_mediumRNN_tracktwoLLP.L1TAU100 HLT_tau180_tightRNN_tracktwoLLP.L1TAU100 HLT_tau200_tightRNN_tracktwoLLP.L1TAU100 HLT_tau180_mediumRNN_tracktwoLLP.L1eTAU140 HLT_tau200_mediumRNN_tracktwoLLP.L1eTAU140 HLT_tau180_tightRNN_tracktwoLLP.L1eTAU140 HLT_tau200_tightRNN_tracktwoLLP.L1eTAU140
(ATR-21797)	HLT_tau80_mediumRNN_tracktwoMVA_tau60_mediumRNN_tracktwoMVA_03dRAB.L1TAU60_2TAU40 HLT_tau80_mediumRNN_tracktwoMVABDT_tau60_mediumRNN_tracktwoMVABDT_03dRAB.L1TAU60_2TAU40 HLT_tau80_mediumRNN_tracktwoMVABDT_tau60_mediumRNN_tracktwoMVABDT_03dRAB.L1eTAU80_2eTAU60 HLT_tau80_mediumRNN_tracktwoMVA_tau35_mediumRNN_tracktwoMVA_03dRAB30.L1TAU60_DR-TAU20ITAU12I HLT_tau80_mediumRNN_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB30.L1TAU60_DR-TAU20ITAU12I HLT_tau80_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB30.L1eTAU80_2cTAU30M_DR-eTAU30eTAU20 HLT_tau35_mediumRNN_tracktwoMVA_tau25_mediumRNN_tracktwoMVA_03dRAB30.L1DR-TAU20ITAU12I-J25 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1DR-TAU20ITAU12I-J25 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1cTAU30M_2cTAU20M_DR-eTAU30eTAU20-jJ55 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1cTAU30M_2cTAU20M_DR-eTAU30MeTAU20M-jJ55
2tau + j support	HLT_tau35_mediumRNN_tracktwoMVA_tau25_mediumRNN_tracktwoMVA_03dRAB30.L1DR-TAU20ITAU12I HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1DR-TAU20ITAU12I HLT_tau35_mediumRNN_tracktwoMVA_tau25_mediumRNN_tracktwoMVA_03dRAB.L1TAU20IM_2TAU12IM HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB.L1TAU20IM_2TAU12IM HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB.L1TAU20IM_2TAU12IM HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1cTAU30M_2cTAU20M_DR-eTAU30eTAU20 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB30.L1cTAU30M_2cTAU20M_DR-eTAU30MeTAU20M HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB.L1cTAU30M_2cTAU20M

⁷ The Menu is in this file: [Physics.pp_run3_v1](#)

ATR-20450	HLT_tau35_mediumRNN_tracktwoMVA_tau25_mediumRNN_tracktwoMVA_03dRAB_L1TAU20IM_2TAU12IM_4J12p0ETA25 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB_L1TAU20IM_2TAU12IM_4J12p0ETA25 HLT_tau35_mediumRNN_tracktwoMVABDT_tau25_mediumRNN_tracktwoMVABDT_03dRAB_L1cTAU30M_2cTAU20M_4jJ30p0ETA25 HLT_tau40_mediumRNN_tracktwoMVA_tau35_mediumRNN_tracktwoMVA_03dRAB_L1TAU25IM_2TAU20IM_2J25_3J20 HLT_tau40_mediumRNN_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB_L1TAU25IM_2TAU20IM_2J25_3J20 HLT_tau40_mediumRNN_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB_L1cTAU35M_2cTAU30M_2jJ55_3jJ50
2tau+j support	HLT_tau40_mediumRNN_tracktwoMVA_tau35_mediumRNN_tracktwoMVA_03dRAB_L1TAU25IM_2TAU20IM HLT_tau40_mediumRNN_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB_L1TAU25IM_2TAU20IM HLT_tau40_mediumRNN_tracktwoMVABDT_tau35_mediumRNN_tracktwoMVABDT_03dRAB_L1cTAU35M_2cTAU30M
Displaced tau+X ATR-21754	HLT_tau80_mediumRNN_tracktwoLLP_tau60_mediumRNN_tracktwoLLP_03dRAB_L1TAU60_2TAU40 HLT_tau80_mediumRNN_tracktwoLLP_tau60_tightRNN_tracktwoLLP_03dRAB_L1TAU60_2TAU40 HLT_tau80_tightRNN_tracktwoLLP_tau60_tightRNN_tracktwoLLP_03dRAB_L1TAU60_2TAU40 HLT_tau100_mediumRNN_tracktwoLLP_tau80_mediumRNN_tracktwoLLP_03dRAB_L1TAU60_2TAU40 HLT_tau80_mediumRNN_tracktwoLLP_tau60_mediumRNN_tracktwoLLP_03dRAB_L1eTAU80_2eTAU60 HLT_tau80_mediumRNN_tracktwoLLP_tau60_tightRNN_tracktwoLLP_03dRAB_L1eTAU80_2eTAU60 HLT_tau80_tightRNN_tracktwoLLP_tau60_tightRNN_tracktwoLLP_03dRAB_L1eTAU80_2eTAU60 HLT_tau100_mediumRNN_tracktwoLLP_tau80_mediumRNN_tracktwoLLP_03dRAB_L1eTAU80_2eTAU60
Single Tau Support Chains	HLT_tau0_ptonly_L1TAU8 HLT_tau0_ptonly_L1TAU60 HLT_tau20_mediumRNN_tracktwoMVABDT_L1TAU8 HLT_tau25_idperf_tracktwoMVABDT_L1TAU12IM HLT_tau25_perf_tracktwoMVABDT_L1TAU12IM HLT_tau25_mediumRNN_tracktwoMVABDT_L1TAU12IM HLT_tau25_mediumRNN_tracktwoLLP_L1TAU12IM HLT_tau60_mediumRNN_tracktwoMVABDT_L1TAU40 HLT_tau80_mediumRNN_tracktwoMVABDT_L1TAU60 HLT_tau160_idperf_tracktwoMVABDT_L1TAU100 HLT_tau160_perf_tracktwoMVABDT_L1TAU100

Monitoring and backup MVA	HLT_tau25_idperf_tracktwoMVA.L1TAU12IM HLT_tau25_perf_tracktwoMVA.L1TAU12IM HLT_tau25_mediumRNN_tracktwoMVA.L1TAU12IM HLT_tau160_idperf_tracktwoMVA.L1TAU100 HLT_tau160_perf_tracktwoMVA.L1TAU100 HLT_tau160_mediumRNN_tracktwoMVA.L1TAU100 HLT_tau200_mediumRNN_tracktwoMVA.L1TAU100 HLT_tau35_idperf_tracktwoMVA.L1TAU20IM HLT_tau35_idperf_tracktwoMVABDT.L1TAU20IM HLT_tau35_perf_tracktwoMVA.L1TAU20IM HLT_tau35_perf_tracktwoMVABDT.L1TAU20IM HLT_tau35_mediumRNN_tracktwoMVA.L1TAU20IM HLT_tau35_mediumRNN_tracktwoMVABDT.L1TAU20IM
ATR-2436	HLT_tau80_idperf_tracktwoMVABDT.L1TAU60
Phase I	HLT_tau0_ptonly.L1eTAU12 HLT_tau0_ptonly.L1eTAU80 HLT_tau20_mediumRNN_tracktwoMVABDT.L1eTAU12 HLT_tau25_idperf_tracktwoMVABDT.L1cTAU20M HLT_tau25_perf_tracktwoMVABDT.L1cTAU20M HLT_tau25_mediumRNN_tracktwoMVABDT.L1cTAU20M HLT_tau25_mediumRNN_tracktwoLLP.L1cTAU20M HLT_tau60_mediumRNN_tracktwoMVABDT.L1eTAU60 HLT_tau80_mediumRNN_tracktwoMVABDT.L1eTAU80 HLT_tau160_idperf_tracktwoMVABDT.L1eTAU140 HLT_tau160_perf_tracktwoMVABDT.L1eTAU140 HLT_tau25_idperf_tracktwoMVABDT.L1eTAU20 HLT_tau25_idperf_tracktwoMVABDT.L1eTAU20M HLT_tau25_perf_tracktwoMVABDT.L1eTAU20 HLT_tau25_perf_tracktwoMVABDT.L1eTAU20M HLT_tau25_mediumRNN_tracktwoMVABDT.L1eTAU20 HLT_tau25_mediumRNN_tracktwoMVABDT.L1eTAU20M HLT_tau35_idperf_tracktwoMVABDT.L1cTAU30M HLT_tau35_perf_tracktwoMVABDT.L1cTAU30M HLT_tau35_mediumRNN_tracktwoMVABDT.L1cTAU30M

Table 4: Tau Menu 2021.