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Trabajo de Tesis Doctoral

My thesis title

My subtitle

Autor:
Francisco SILI

Directores:

Prof. Dr. Maria Teresa DOVA
Dr. Francisco ALONSO

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En memoria de Ayla, que todos los dias me ilumina.
A mis papás y hermano, por su infinito amor.

ACKNOWLEDGEMENTS

akwnoelasdfsa

I, Francisco SILI, hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

La Plata,
2nd September 2024

Francisco SILI

Universidad Nacional de La Plata
Facultad de Ciencias Exactas
Instituto de Física La Plata

TESIS DE DOCTORADO

My thesis title

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by Francisco SILI

ABSTRACT

some text

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0.1 To Do's and notes to keep in mind

use **orange** to highlight that there needs to be made sure that there is a discussion in previous chapters - in editing clarify where that discussion should happen!
purple: this needs a reference, have used from memory or notes
red: open question

0.1.1 Fixes, to dos

- test
- need to include a definition on met in the object definition part?

0.1.2 Thoughts to work with

- have to be consistent with times in the description - discuss with Fab about it

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- how is the reconstruction considered overall? are there different

Introduction

This thesis presents a search for new phenomena in high-mass final states with a photon and a jet in proton-proton (*pp*) collisions at a centre-of-mass energy of 13 TeV using data collected by the ATLAS detector. ATLAS ("A Toroidal LHC ApparatuS") is one of the two general-purpose detectors at the Large Hadron Collider (LHC) and the biggest multi-purpose particle detector ever built. It is used to investigate a wide range of physics, from Standard Model (SM) measurements, such as precision tests of quantum chromodynamics or study of the properties of the Higgs boson, to the search of new phenomena like extra dimensions and dark matter candidates. The LHC, built by the European Organization for Nuclear Research (CERN) and installed in a 27-kilometre circular tunnel, is the world's largest and most powerful particle collider. This machine is capable of colliding energetic beams of protons (or heavier nuclei) at rates upward of millions per second. The precision and high beam energy of the LHC allow to explore the tera-electronvolt scale, an energy range never before achieved in a particle collider.

The thesis is divided into three parts. The first part describes the theory background and motivations of the work, in which the first chapter describes the Standard Model (SM) showing the excellent agreement there is between the theory and the experimental data. It also shows the actual problems of the SM, which motivates the search for New Physics.

The second part describes the experiment. CHAPTER describes the ATLAS experiment, with each sub-detector in detail, to finally describes how the samples for data analysis are produced. The reconstruction of the different physics objects is explained in CHAPTER. At the end of the second part, a special chapter is dedicated to the photon identification, where a new method for correcting the shower shapes is explained and detailed.

The third part of the thesis is dedicated to the photon+jet resoanance search. In CHAPTER, the general strategy and motivation of the search is discussed. The samples generation is discussed in CHAPTER, where the final event selection is given in CHAPTER. The methods for the background estimation as well as background modeling is given in CHAPTER AND CCHAPETER. The systematic uncertainties are discussed in CHAPTER, and finally in CHAPTER and CHAPTER, the statistical analysis with the results are shown.

Finally, the conclusions of the work are present in CHAPTER.

Part I

Theory Motivation

1 THE STANDARD MODEL AND BEYOND

"Nothing in life is to be feared. It is only to be understood. Now is the time to understand more, so that we may fear less"

Marie Curie

another template text

Part II

Experimental setup

The ATLAS Experiment

2

Ignore the glass ceiling and do your work. If you're focusing on the glass ceiling, focusing on what you don't have, focusing on the limitations, then you will be limited.

Ava DuVernay

2.1 LHC

FIGURES AND REFERENCES

The Large Hadron Collider (LHC) [1, 2] is the largest hadron accelerator in the world, located at European Organization for Nuclear Research (CERN), in the French-Swiss border. It has a longitude of 27 km, located between 50 and 174 meters underground. The LHC is designed to collide protones (and heavy ions) at a center of mass energy of 14 TeV. To keep the protons and heavy ions on the accelerator ring, overall 9593 magnets are used. These magnets include superconducting dipole and quadrupole magnets, cooled down to 1.9 K (-271 $^{\circ}C$). The dipole magnets generate a magnetic field of 8.3 T. The protons are sourced from hydrogen gas by stripping its electrons and are accelerated in a first linear accelerator (LINAC2) to 50 MeV. Subsequently, the protons are successively accelerated in the Proton Synchrotron Booster (PSB), the Parton Shower (PS), and the Super Proton Synchrotron (SPS), where they reach an energy of 450 GeV before being injected into the LHC. Overall 8 radiofrequency cavities can push the energy of the protons in the LHC up to 14 TeV.

The protons are injected as bunches of $\mathcal{O}(10^{11})$ protons into the LHC with a spacing of 25 ns (7.5 m). These bunches are later brought to collision in so-called bunch crossings. The filling scheme of the pre-accelerator chain, in combination with finite switching times of the injection and dumping magnets, results in regular patterns of filled and empty bunches.

The LHC so far provided proton and heavy ion beams for two data-taking periods, and is undergoing a third. Between 2009 and 2013 (known as Run 1), the LHC was operating with a centre-of-mass energy ($\sqrt{s}$) of 7 TeV and 8 TeV. After a long shutdown (LS1), the second run (Run 2) started in 2015 and ended in 2018, providing 13 TeV collisions to the experiments around the LHC ring. In 2022 the Run-3 started, at which *pp* collisions happen at an energy of 13.6 TeV, estimated to run until 2026. In Figure FIGURE visualised yellow dots, there are four interaction points, housing the ALICE [3], LHCb [4], CMS [5], ATLAS [6], LHCf [7] , TOTEM [8], MoEDAL [9] experiments, among many other experiments.

One of the most important parameters to characterize the functioning of the accelerator is the instantaneous luminosity $\mathscr{L}$, defined as the number of particles per unit time per unit area, and can be calculated from the relation

$$\mathscr{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi\epsilon_n \beta^*} F \tag{2.1}$$

where N_b is the number of particles per bunch, n_b the bunches per beam, γ_r is the relativistic gamma factor, ϵ_n is the normalised transverse beam emittance and β^* bein the beta function at the collision point which determining the transverse spread of the particle beam. The correction term F takes into account the beam crossing angle. The revolution frequency is represented by f_{rev} which is ~ 11 kHz, and with the bunch-spacing of 25 ns, allows for beam crossing at the four interaction points with a frequency of ~ 40 MHz.

A measure for the total recorded data is the integrated luminosity over time is given by

$$N_{event} = L_{int}\sigma_{event} = \sigma_{event} \int \mathscr{L} dt, \tag{2.2}$$

connecting the luminosity with the number of events. This can be seen for each month during Run 2 in FIGURE. This illustrates the overall 156 fb^{-1} of a proton-proton collisions delivered to A Toroidal LHC ApparatuS (ATLAS) by the LHC as well as the 139 fb^{-1} of data collected by ATLAS with detector conditions good enough to use the events in data analysis. Combining the 2022, 2023 and 2024 years of data taking for Run-3, XX fb^{-1} of data was recollected.

A high instantaneous luminosity comes with the challenge of pile-up, i.e. multiple *pp* interactions per bunch crossing. During Run 2, the average number of simultaneous interactions per bunch crossing (μ) varied between approximately 10 and 60, depending on the run conditions, with an overall average of 34. Pile-up collisions pose challenges to the trigger and event reconstruction to distinguish their effects from the interaction of interest.

2.2 ATLAS

ATLAS is one of the multi-purpose detectors of the LHC, located at Point-1 along the LHC. It was designed and built to study the *pp* (and heavy ion) collisions at the TeV scale.

The overall shape of the detector is that of a cillinder. Shown in FIGURE, the detector has a length of 44m and 25m in diameter, being the largest particle detector built so far. The ATLAS detector is divided geometrically in two parts: the central part called *barrel*, and the outer caps called *end-caps*.

ATLAS is built in layers of sub-detectors, each of which designed to have a different role on the identification and reconstruction of particles produced in the collisions. ATLAS provides hermetic coverage around the beam axis, enabling detection of all charged particles generated in the collisions in the plane orthogonal to the beam axis. This is particularly important in searches for new physics, relying on analyses of momentum balances in the orthogonal plane such as discussed within this thesis.

It is built up of multiple layers, starting from the innermost component, the Inner Detector (ID), providing tracking hits close to the beam pipe. Around the ID, there is a superconductor solenoid which creates an axial magnetic field of ~ 2 T to curve the ID tracks of charged particles After the first magnet, there is a system of two calorimeters: the Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL). The former is in charge of measuring the kinetic energy of photons and electrons, and the latter measures the energy of the jets. The outermost parts of ATLAS are built by the muon spectrometer, providing momentum reconstruction for muons passing through the inner detector layers. Intertwined with the muon spectrometer, there are a total of 8 barrel toroid coils, providing a total magnetic field of 4 T (0.5 T per coil) to measure the momentum of muons. The toroid magnetic field is completed by the end-cap toroids, also generating a magnetic field up to 4T for muons leaving ATLAS close to the beam pipe.

Every component in ATLAS working together enables the reconstruction and identification of a variety of particles with high precision. An overview of the design capabilities of ATLAS in terms of the momentum and energy resolution is given in TABLE, adapted from Ref. [6]. Here the resolution given lists first a stochastic term, measuring the uncertainty based on the statistically dominated interaction of a particle with the material, followed by a noise term, which accounts for uncertainties due to electronic noise in the readout process.

2.2.1 ATLAS Coordinate system

The coordinate system used within ATLAS is used throughout this thesis and shortly described in the following [6]. The origin of the right-handed coordinate system is at the nominal interaction point, with the positive x-axis pointing towards the centre of the LHC. The x-y plane is perpendicular to the beam axis, defining the z-axis. Towards the surface defines the positive y-axis. An azimuthal angle ϕ is defined around the beam axis, and a polar angle θ is the angle from the beam axis. Instead of θ the rapidity y is used for heavy objects:

$$y = \frac{1}{2}\ln[(E + p_z)/(E - p_z)] \tag{2.3}$$

Differences in Rapidity are invariant under boosts along the beam axis. For massless objects or relativistic objects ($m << \boldsymbol{p}$), the pseudorapidity is used:

$$\eta = -\ln\Big(\tan(\theta/2)\Big) \tag{2.4}$$

To quantify the distance between two objects, ΔR is defined:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \tag{2.5}$$

The transverse momentum and energy are defined in the x-y plane, with the transverse momentum given as $p_T = \sqrt{p_x^2 + p_y^2}$.

2.2.2 Inner Detector

A cross-section of the ID system [10] is shown in FIGURE, highlighting the distance of each subsystem from the beampipe. The innermost part of the ID is the Insertable B-Layer (IBL), followed by three layers of pixel detectors. At 299 mm radial distance from the beam pipe, four layers of SemiConductor Tracker (SCT) modules are located before the Transition Radiation Tracker (TRT), which extends the overall ID detector size to a radius of 1082 mm. The ID allows for particle track reconstruction within $|\eta| < 2.5$.

The role of the ID is the trajectory tracking of changed particles to determine their charge and momentum. It is immersed in a 2 T magnet field generated by the ATLAS solenoid magnet system, that bends the trajecories of charged particles. The curvature radius is proportional to the particle momentum and its direction distinguishes positive from negative charges. The detected particle tracks allow for the reconstruction of primary collision vertices, which is important to distinguish pile-up collisions from the collision of interest, and of secondary decay vertices of longer-lived particles, which is crucial for the identification of e.g. B mesons or τ leptons.

IBL - Insertable B-layer After Run-1, during a long shutdown in 2013-2014, the pixel detector system was subject to maintenance and upgrades. Within this set of upgrades, a 4th pixel layer at a 3.3 cm distance from a new, smaller beam pipe (33 mm outer radius, originally 36 mm). A fourth pixel layer was a first in particle physics experiments CITE and has led to significant improvements in interaction vertex reconstruction and identification of b-hadron jets.

Pixel Detector The innermost pixel layer, the IBL, is surrounded by three layers of pixel detectors, arranged in barrels around the beam pipe [11, 12]. The method of detection of charged particles is the measurement of deposited induced charges in a silicon layer, product of ionization. The first layer is at a distance of 50.5 mm from the beam pipe's centre. As can be seen in FIGURE, the end caps of the pixel layer consist of 3 disks around the beampipe, stretching the length of the pixel component of the ID to 1.4 m length along the beam axis. The pixel detector consists of overall 1744 pixel modules with a nominal size of $50\mu m x 400\mu m$ in the (ϕ, z) plane (ϕ, r for the disk panels), comprising over 80 million readout channels. The pixel and IBL part of the ATLAS detector is crucial for tracking, providing 4 pixel hits over the entire ID pseudorapidity coverage ($|\eta| < 2.5.$).

Semiconductor Tracker The pixel detector and IBL are located within SCT modules [13]. Similar to the pixel detector modules, the SCT modules are semiconductor-based, arranged into cylindrical layers around the beampipe in the barrel region, forming disks in the endcap. Since the SCT modules only provide precise location along one axis, two modules are combined back-to-back and rotated against each other to gain two dimensional spacial information. Four layers are arranged in the barrel, nine disks in each endcap side (see FIGURE). Including the endcap disks, the SCT extends up to $|z| < 2735mm$.

Transition Radiation Tracker The last part of the ID is the TRT [14], in the barrel stretching from 554 mm to 1082 mm radial distance. This detector is composed of 4 mm diameter straw tubes, arranged in parallel to the beam pipe or radially in the barrel and end-cap, respectively. Within $|\eta| < 2.0$, three barrel rings and 18 end-cap units provide typically 36 hits per track. The straws are intertwined with polypropylene fibres for passing through particles to create transition radiation. Inside the straws is a thin tungsten wire, collecting charges drifting through the straws gas mixture (Xe, CO2 and O2). The level of radiation and collected charges in each straw can be used to discriminate between electrons and charged pions. The TRT only offers spatial information in the $(R-\phi)$ plane, no information in the z-direction can be extracted due to the straws orientation. There is a total of 50000 tubes in the barrel region, while the end-caps contain 320000 tubes.

2.2.3 Calorimeters

As previously mentioned, the ID system is surrounded by two calorimeters: the ECAL and the HCAL. These calorimeters are designed to measure the energy and position of the incident particles, via the deposited energy by the secondary particle cascades produced by the incident ones. It covers the whole ϕ range and up to $|\eta| < 4.9$, with a finer granularity in the region that coincides with the ID. The calorimeter system allows for the discrimination between photons and electrons from hadrons (jets). Furthermore, it allows to measure the energetic imbalance (thanks to its total coverage and hermiticity) and it provides the trigger system with the necessary information for the event selection.

Both calorimeters are so-called sampling calorimeters with alternating layers of absorber and active material. The absorber layer triggers a shower development of consecutive interactions with the detector material, the active layer is detecting the signal. The shower development and properties are of vital importance for the particle identification, as it will be shown later. Two important quantities in connection with the calorimeters are the radiation length, X_0, and the interaction length λ. The radiation length refers to the distance after which an electrons energy has been reduced to $1/e$ of its initial energy. The interaction length describes the mean free path before the occurrence of an hadronic interaction.

The design resolution of the system on the calorimetric energy is given by

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \tag{2.6}$$

where $\oplus$ means that the terms are summed in quadrature. The stochastic term $\frac{a}{\sqrt{E}}$ is related with the fluctuations on the shower developments, the constant term b takes into account the inhomogeneities of the detector, and the last term is associated with the electronic noise and is proportional to $\frac{1}{E}$. The value of the coefficients a amd b depend on the incident objects. For the electrons' case in the ECAL, $a \sim 10\%$ GeV$^{1/2}$ and $b \sim 0.7\%$, while those for charged pions in the center of the detector are $a \sim 50\%$ GeV$^{1/2}$ and $b \sim 5\%$ [15].

Electromagnetic Calorimeter - ECAL

The ECAL specializes on the detection of electrons, positrons and photons, which deposit their energy in relatively dense showers: energetic electrons that radiate Bremsstrahlung photons, while energetic photons convert to electron-positron pairs when traversing the dense material. The absorber is made of lead (Pb) with stainless steel sheets, while Liquid Argon (LAr) is used as the active material with copper and kapton electrodes for readout.

The calorimeter has an accordion geometry which provides complete ϕ symmetry without azimuthal cracks. It is divided into two half barrels covering the central detector region ($|\eta| < 1.475$), with a small (4 mm) gap at $z = 0$ and one end-cap on each side of the beamline ($1.375 < |\eta| < 3.2$) (see FIGUE). The transition region between the barrel and end-cap is called as the *crack* region, and the majority of physics analysis using the ECAL require that the photons and electrons are outside of it. Additionally, the LAr technology is used for the hadronic calorimeters end-caps as well as a Forward Calorimeter (FCAL) ($3.1 < \eta < 4.9$).

The thickness of the ECAL is over 22 radiation lengths (X_0) in the barrel region, while over $24X_0$ in the end-cap region. For photons, the distance at which the energy dropped to $1/e$ is $9/7X_0$, therefore all the photon's electromagnetic energy is deposited in the ECAL, and only a small part reaches the HCAL.

The mode of measurement is as follows. The incident particles interact with the absorbent medium (Pb), initiating a shower of charged and neutral particles. The charged particles ionize the LAr medium and the electrodes, with the help of an applied magnetic field, collect the electrons produced in the ionization process. The total signal of the active medium is then proportional to the total real energy of the incident particle.

Within the region accepted for precision measurements ($|\eta| < 2.5$ excluding the crack), the ECAL is segmented in three longitudinal layers. The first layer consists on fine-granularity bands (also called the strip layer) which helps with the discrimination between isolated photons and pairs of photons spacialy closed originating from $\pi^0 \to \gamma\gamma$ decays. This layer has a constant thickness of $\sim 6X_0$ as a function of η, and provides a precise measurement of this variable. For high energy photons and electrons, the majority of their energy is collected in the second layer, which has a lateral granularity of 0.025×0.025 in (η, ϕ) and a thickness of $\sim 24X_0$. The third layer collects the energy deposited by the tails of the electromagnetic shower, with thickness that varies between 2 and 12 X_0. There is also a presampler (not shown in figures), that covers the region $|\eta| < 1.8$ that improves the energy measurement for particles that start showering before entering the calorimeter.

Hadronic Calorimeter - HCAL

Three hadronic calorimeter layers surround the ECAL and provide additional discrimination for electrons and photons when measuring the hadronic energy. The HCAL extends in pseudorapidity up to $|\eta| < 4.9$, allowing virtually the entirety of the solid angle to be covered from the interaction point. In the barrel region ($|\eta| < 1.7$), the tile calorimeter, a sampling calorimeter using steel as absorbing material and plastic scintillator tiles as active material [16], is located. It is divided into two parts ($|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$). The scintillators, arranged in a periodic array, are connected to an optical fiber that carries the light produced by the passing particles to a photomultiplier tube. This array extends, in R, from 2.28 to 4.25 m. In the endcap region ($1.5 < |\eta| < 3.2$) is a hadronic sampling calorimeter (HEC) with copper plates as absorber and liquid argon as active material. Each side of the endcap consists of two wheels, one behind the other with the flat Cu plates arranged perpendicular to the beam axis, with a radius of 2.3 m. Finally there is the FCAL, a sampling calorimeter that extends the coverage of the system to $|\eta| < 4.9$, coaxial to the beam axis and located 4.7 m on either side of the interaction point. The main material of the modules is LAr (with copper or tungsten), and while not used for precision measurements, it provides information for computation of the missing transverse energy and reconstruction of jets in regions very close to the beam axis.

The HCAL has a thickness greater than 7.7 λ in the barrel region (9.7 λ in total if the ECAL is counted). Analogous to the radiation length mentioned for the ECAL, a hadronic interaction length is defined as the average distance over which the energy of a hadron is reduced to $1/e$ of its initial energy. Thus, all the energy with which the hadrons arrive at the HCAL is deposited there.

2.2.4 Muon spectrometer

The high p_T muons generated at the interaction point have very high penetrating power and are poorly interacting. Therefore the Muon Spectrometer (MS) [17] is located in the outermost part of the ATLAS detector, embedded within the 4 T magnetic field generated by the barrel and endcap toroid magnets, and is designed to obtain high precision position and momentum measurements of high p_T muons. This is the largest subdetector and the one that gives ATLAS its size.

In FIGURE, a quarter of the muon system is visualised, highlighting the different subsystems. Monitored Drift Tubes (MDTs) and Resistive-Plate Chambers (RPCs) form three layers around the barrel,Cathode Strip Chambers (CSCs) are used close to the beam pipe. The *Big Muon wheels*, forming the "lids" of the ATLAS barrel structure, are comprised of Thin-Gap Chamber (TGC) and MDT subdetectors.

The MS is designed to precisely measure muons within $|\eta| < 2.7$ and to provide muon trigger information up to $|\eta| < 2.4$. It consists on three layers of MDTs in the barrel and up to four layers in the endcaps. They cover the pseudorapidity range up to $|\eta| < 2.7$, providing high precision track coordinates perpendicular to the magnetic field. In the innermost end-cap layer, the MDT chambers are replaced by CSCs, as they perform better at the high rates of the more forward regions[1]. The barrel layers are additionally equipped with RPCs and the endcap layers with RPC. These provide a coarse, quick, secondary coordinate measurement.

If hits in the ID and the MS can be associated with a single muon, a very good momentum resolution of up to

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = 0.02\% \cdot p_{\mathrm{T}}\,[\mathrm{GeV}] \oplus 2\% \tag{2.7}$$

is achieved. The momentum resolution degrades accordingly if a track is identified in only one of the two systems.

2.2.5 The Trigger System

The ATLAS trigger system [19–21] uses information from the detector to reject events that do not possess interesting physics (physics already known for example), reducing the event frequency from 40 MHz (bunch-crossing frequency mentioned in Section 2.1) to around 1.5 kHz. It is necessary to emphasize here the central role of the trigger system for the proper functioning of the whole experiment, being responsible for deciding which events are saved and, ultimately, which physics will be encountered (or not) during the event analysis. Without an efficient trigger system, all the subdetectors described above would be wasted. To achieve such a reduction in event frequency and, at the same time, have a high efficiency in selecting those of interest, the trigger system is composed of two consecutive levels capable of performing increasingly complex particle identification; a first hardware-based trigger level, Level-1 (L1), and then a high-level software-based trigger, the High Level Trigger (HLT). Each level allows events to be analyzed in greater detail, increasing the accuracy of the selection criteria and the complexity of the algorithms used.

Level-1 trigger

The trigger decision starts with the hardware-based L1 trigger [22], which identifies Region of Interests (ROIs). These ROI consist of neighbouring cells in the ECAL and HCAL and are defined from the position in the calorimeter of each object found in a potentially interesting event, which extends as a cone from the interaction point along the detector. Regarding muons, it takes the information read by the MS, more specifically the TGC and RPC and allows to obtain a fast estimate of the muon p_{T}. The L1 trigger also has a component that allows for topological requirements such as invariant mass selections and distance measures to be taken into account in the L1 decision, referred as the Level-1 Topological (L1Topo).

The design of the L1 allows to have an acceptability in the range of $|\eta| < 2.5$ for electrons, photons, muons and taus, up to $|\eta| < 3.2$ for jets, and $|\eta| < 4.9$ for the missing transverse momentum calculation. Using the ROIs, the L1 trigger must make the decision to keep or discard

[1] The innermost End-Cap layer has been replaced with the ATLAS New Small Wheel (NSW) after Run 2 [18]. It features MicroMegas as precision trackers as they provide better performance at the high rates expected in future LHC operations.

the event, reducing the event rate from 40 MHz to less than 100 kHz in approximately 2.5 μs, time determined in part by the limited size of the memory buffers and in part by the time it takes for the muons produced in the event to reach the MS. This final decision is done by the Central Trigger Processor (CTP), and then passes the ROIs to the next trigger level: the HLT.

The High Level Trigger

When an event is accepted by the L1, the HLT [23] executes a sequence of algorithms starting from the ROIs defined by the L1, and allows to reduce the event rate that is stored at 1.5 kHz in 0.2 s. The reconstruction and identification of candidate particles in the HLT is evaluated in a sequence of steps where different algorithms are applied. If the selection fails in a certain step, the following steps are no longer executed to save execution time. In HLT, the algorithms are grouped into sets of fast reconstruction algorithms executed first, and then a set of precision reconstruction algorithms similar to those used offline are executed, thanks to the latency time available. The fast reconstruction algorithms use the calorimeter and track information from the ID only within the ROI to perform candidate selection and identification, and perform background rejection as quickly and early as possible. If the candidate particle passes the criteria defined by the fast reconstruction selection, precision selection algorithms are run. These have access to detector information outside the RoI, at the highest granularity and including details on calorimeter energy calibration, sub-detector alignment and magnetic field mapping.

The exact sequence and type of algorithms considered at the HLT are defined in the trigger *menu*. This comprises a database of triggers, each trigger defining a sequence of algorithms and requirements on these algorithms for an event to pass the HLT. The overall set of triggers targeting various detector signatures associated with particles, such as electrons, muons or photons as well as missing transverse energy. The trigger requirements are designed and budgeted in a way that the overall HLT rate does not exceed 1 kHz. In some cases, even the reduction in event rate achieved through the HLT algorithms for desired trigger requirements, such as low momentum triggers, is too high. To keep the overall HLT rate below 1 kHz in these cases, triggers can still be included in the menu, but with a prescale. A prescale is an artificial scaling of the trigger, only accepting every Nth trigger decision if the prescale factor is N. This allows triggers with an otherwise high rate to still collect events.

The HLT algorithms run on approximately 40 thousand CPU cores. In addition, partial event construction is used for trigger-level analysis, detector monitoring, and detector subsystem calibrations. Finally, the accepted events by the HLT are saved to a disk and distributed, available *offline* for any study or analysis.

2.3 Data-taking during Run-2

The operation of the LHC is organized into distinct periods known as data-taking Runs. Each run typically spans several years and is characterized by specific experimental conditions, including the energy at which the protons are collided and the intensity of the beams. Since its commissioning, the LHC has undergone multiple data-taking runs: Run-1 (2010-2013) operated at collision energies up to 8 TeV, Run-2 (2015-2018) at 13 TeV, and Run-3 (2022-present) at 13.6 TeV. Each data taking period, once the LHC announces stable beams, is divided into Luminosity-blocks (LBs) of approximately two minutes. At each LB, the instantaneous luminosity is practically constant and the beam conditions are stable. Due to the high complexity of the LHC and the ATLAS detector, it is expected to have inefficiencies in the detectors and sub-detectors and/or in the data acquisition chain. During each Run, each part of ATLAS is monitored and any failure or problem is registered, including inactive components, or problems on the LHC beam.

In order to guarantee the high-quality data, free from significant defects, the LBs and ranges within them that pass all the quality criteria are compiled into Good Runs List (GRL). The lists are produced and distributed in a centralized manner, in order to provide any ATLAS group with the same collection of LBs. Since during the runs different parts of the detector are available (in an optimal run, all of the subdetectors are available), there are multiple GRLs available to use. Each analysis, then, selects which GRL to use depending their tolerance to the subdetectors' faults.

The present thesis uses ATLAS data recollected from pp collissions during the Run-2 (2015-2018), at a centre of mass energy of $\sqrt{s} = 13$ TeV. During this run, the LHC delivered a total of 156 fb^{-1}, from which ATLAS collected 147 fb^{-1}. The total integrated luminoity avaliable for Phyiscs analysis is 140.0 fb^{-1}, as seen from FIGURE.

Another important concept in ATLAS data acquisition is pileup, which occurs when particles produced in more than one pp collision arrive at the detector at the same time, or more generally, when signals overlap in a way that cannot be separated. When bunches of protons collide, the probability of an interaction is proportional to the particle density, or better, to the particle flux, which is expressed by the instantaneous luminosity. The actual number of particle collisions that take place when two bunches intersect is a random variable that follows a Poisson distribution. For low luminosities, in most beam crossings, no collisions occur, but for high instantaneous luminosities, in most crossings many particle collisions occur at the same time. Depending on the subdetector and the type of measurement, it may or may not be possible to distinguish between particles coming from different simultaneous interactions. This is called in-time pile-up. In contrast, out-of-time pile-up includes the effects that arise when the time the detector needs to return to its waiting state is longer than the time between bunches crossing. A quantitative measure of pile-up and event activity is the mean value of pp inelastic interactions per bunches crossing, $\langle\mu\rangle$.

The maximum instantaneous luminosities increased by a factor of four over the four years of

Run-2, resulting in an increase of $\langle\mu\rangle$. The annual values of maximum instantaneous luminosity, $\langle\mu\rangle$, and integrated luminosity after requiring stable beam conditions and a functional detector are summarized in TABLE for *pp* collisions. The uncertainty in the combined integrated luminosity for 2015-2018 is 0.83% [24], obtained using the LUCID-2 detector [25]. In 2017 the maximum $\langle\mu\rangle = 80$ was reached only in a few special runs, so the maximum value for physics analyses is considered with $\langle\mu\rangle = 60$.

Reconstruction and identification of physical objects

3

"Champions keep playing until they get it right."

Billie Jean King

The particles (and products of their decays) produced at every collission, interact with the detector in a particular manner according to their nature. The information recollected by all the sub-detectors described in the previous chapter allow for the reconstruction and identification of the physical objects present in each accepted event by the trigger system. Two types of reconstruction and identification exist. The *online* one, is carried out at the same time the *pp* collissions take place, and the *offline* one, done after the events are saved to storage. The reconstruction is done event by event, and is carried in the same way for events recorded by the ATLAS detector and for simulated Monte Carlo (MC) events. In the following, a brief overview of the offline reconstruction and identification of the objects used in this thesis is given.

3.1 Track and vertex reconstrucion

In a high-pileup event, there can be of the order of 1000 charged particles passing through the ATLAS detector. The information from the ID (Section 2.2.2) is used to reconstruct the trajectories of charged particles, called *tracks*.

Tracking charged particles is a critical step in reconstruction. Tracks encode charged particles' momentum and trajectory, playing an essential role in particle identification and primary vertex reconstruction. As the inner detector is closest to the beamline and comprises minimally ionizing detector material with high granularity, it plays the main role in track reconstruction. A charged particle passing through different layers of ID leaves a signal via ionization. As the ID solenoidal field is homogenous, the resulting trajectory is circular in the xy plane. Five parameters shown in FIGURE define charged particle tracks:

- q/p_{T}: the ratio of the charge and transverse momentum defining the curvature

- d_0: the distance of the closest approach to the primary vertex in xy-plane defining the transverse impact parameter
- z_0: the longitudinal impact parameter along the z-axis
- ϕ_0: the azimuthal angle
- θ_0: the polar angle of the particle direction oat the closest point of approach [26].

The track reconstrucion used in Run-2 uses two complementary approaches: the *inside-out* approach, and the *outside-in* [27].

The first step in the inside-out track reconstruction is the seed-finding, where three hits in the silicon detector are searched for to seed the track reconstruction. Using these three hits and assuming an uniform magnetic field, a first estimate of the track parameters is obtained. Using the track seeds, the track is extrapolated to the other silicon layers, from which a combinatorial Kalman filter is used to estimate the track parameters. At this stage of the process there can be several track candidates for each track seed. Once the track is formed, an ambiguity resolution algorithm is applied to reassign shared clusters to the track with a better match [28], and the final track candidate is fitted using a global χ^2 method. The last part of the inside-out method consists on extending the tracks to the TRT, and including the TRT hits to the track, to improve the track's momentum resolution.

To improve the eciency for tracks from decays displaced from the original collision point, an outside-in track reconstruction algorithm is also used. The track is seeded with hits from the TRT. The track is extended to include hits from the silicon detector, with an ambiguity solver again applied to mitigate the hit sharing between two tracks.

Primary and secondary vertices are of vital importance for the subsequent object reconstruction in ATLAS. In this step, the tracks found as explained previously are used as input to the vertexing algorithm [29,30]. First of all, the Primary Vertex (PV) is defined as the location where two protons collide. PVs are reconstructed by matching up intersecting tracks, which proceeds in three main steps: seeding, track assignment, and fitting. The vertex with the largest $\sum p_{\mathrm{T}}^2$ for all associated tracks is labeled as the hard-scatter vertex. There are some particles that decay rapidly after their production, such as τ leptons or heavier quarks (b or c-quarks), and their decay position can be measured. From the remaining tracks originated from these decays, it is possible to identify secondary vertices. All the remaining reconstructed vertices are considered to be pile-up.

3.2 Photons and electrons

The reconstruction of electrons and photons in ATLAS is based on the energy deposition in the ECAL. Since electrons and photons leave similar signals in the ECAL, their reconstrucion is done simultaneously, distinguishing between them by the reconstructed track information left in the ID.

3.2.1 Reconstruction

The *offline* photon and electron reconstruction [31, 32] makes use of dynamic, variable-size clusters, connected topologically between the ECAL and HCAL cells [33], called topo-clusters. This approach allows for the clusters to recover energy from bremsstrahlung photons or from electrons from photon conversions.

There are three types of objects:

- Electrons: consists of a cluster built from the energy deposits in the ECAL and a matched track.
- Converted photons: consits of a cluster mathed to a conversion vertex (or vertices)
- Unconverted photons: cluster matched to neither an electron track nor a conversion vertex.

The algorithm for the reconstruction of electrons and photons proceeds as shown in FIGURE.

The reconstruction process begins with the topo-cluster formation. First, proto-clusters are formed in the ECAL and HCAL by grouping cells that have a required energy, and by subsequently adding neighbouring cells in four consecutive steps, obtaining the topo-cluster. Reconstructions starts only in those cases where the topo-clusters energy in the ECAL is greater than 400 MeV.

The algorithm also builds conversion vertices out of the refitted tracks and matches them to the selected topo-clusters. After the initial track-cluster matching and conversion building, the electron and photon supercluster algorithms run separately in parallel. In the first stage, topo-clusters are evaluated for use as seed cluster candidates, which form the basis of superclusters; in the second stage, clusters near the seed candidates are identified as satellite cluster candidates, which may emerge from bremsstrahlung radiation or topo-cluster splitting. Satellite clusters are added to the seed candidates to form the final superclusters, if they pass the necessary selection criteria After applying initial position corrections to the resultant superclusters, the reconstruction algorithm matches tracks to the electron superclusters and conversion vertices to the photon superclusters.

Since one object may be reconstructed as both an electron and a photon, an ambiguity resolution is performed to remove part of the overlap. However, some overlap is allowed in order to maintain a high reconstruction efficiency for electrons and photons, to which physics analyses may apply their own criteria. The final electrons and photons are then built and calibrated, facilitating the calculation of additional variables used for quality cuts and ambiguity resolution

3.2.2 Identification

In order to distinguish real photons (those coming from the collision) from background photons which have much larger production cross sections (coming from hadrons decays, also called fake photons), it is necessary to rely on a algorithm of identification with high signal efficiency and background rejection, for photon candidates with $p_{\mathrm{T}} \sim 10$ GeV up to the TeV scale. Currently, photon identification in ATLAS is based on a set of rectangular cuts on Shower Shape Variables (SSVs) computed from the energy deposited in the cells of the cluster in the first and second layer of the ECAL, and from the leakage to the HCAL. These variables describe the passage of the photons through the calorimeters, characterizing the lateral and longitudinal electromagnetic showers. In general, real photons produce narrower energy deposits in the ECAL, and have lower leakages to the HCAL, compared to those photons provenінent from hadrons. The reason behind this behaviour is the presence of additional neighbouring hadrons close to the fake photon. Furthermore, since the first layer of the ECAL consists on fine strips, it is possible to discriminate photon candidates coming from $\pi^0 \to \gamma\gamma$ decays, characterized by two local maxima due to the presence of two nearby photons.

In the following, the SSVs used for photon identification are detailed. The first variable makes use of the energy measured in the HCAL:

- Hadronic leakage: is the trasnverse energy deposited in the HCAL, normalized to the energy deposited in the ECAL:

$$R_{\mathrm{had}\,(1)} = \frac{E_{\mathrm{T}}^{\mathrm{had}}}{E_{\mathrm{T}}^{\mathrm{EM}}} \tag{3.1}$$

  In order to minimize the effects of resolution degradation, in the barrel-endcap transition region of the HCAL ($0.8 \leq |\eta| \leq 1.37$) the energy deposit in the whole HCAL is used (R_{had}). On the reminaing of the detector, only the energy deposited in first layer of the HCAL is used ($R_{\mathrm{had}\,1}$).

The following variables use the second-layer information of the ECAL:

- Lateral energy profile in η:

$$R_{\eta} = \frac{E_{3\times7}^{s2}}{E_{7\times7}^{s2}} \tag{3.2}$$

  where $E_{i\times j}^{s2}$ is the energy sum in the second calorimeter layer contained in a window of $i \times j$ cells (units of $\eta \times \phi$ cells), centered at the most energetic cell. This variable gives a measure of the showers' width in the η direction.

- Lateral energy profile in ϕ:

$$R_{\phi} = \frac{E_{3\times3}^{s2}}{E_{3\times7}^{s2}} \tag{3.3}$$

  defined in a similar way as R_{η}. However, this variable behaves very different for converted and unconverted photons. Due to the action of the magnetic field, the electrons and positros are curved into opposite directions in ϕ, having as a result, electromagnetic (EM) showers much wider in the case of converted photons than those for unconverted ones.

- Lateral shower width in η:

$$w_{\eta 2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i}\right)^2} \tag{3.4}$$

measures the proper width of the EM shower, where E_i is the energy in the i-th cell of the ECAL, measured in a window of 3×5 cells in $\eta \times \phi$.

Photon identification and shower shape corrections

4

"Champions keep playing until they get it right."

Billie Jean King

yet another template (yat)

Part III

New Physics

5 ANALYSIS MOTIVATION AND STRATEGY

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6 Signal and Background samples

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7 EVENT SELECTION

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Background estimation

8

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9 Background modeling

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10 Systematic uncertainties

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STATISTICAL ANALYSIS 11

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12 RESULTS

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CONCLUSIONS

Don't let anyone rob you of your imagination, your creativity, or your curiosity.

Mae Jemison

Glossary

ALICE A Large Ion Collider Experiment

ATLAS A Toroidal LHC ApparatuS 7

CERN European Organization for Nuclear Research 6

CMS Compact Muon Solenoid

CSC Cathode Strip Chamber 12

CTP Central Trigger Processor 14

ECAL Electromagnetic Calorimeter 8

EM electromagnetic 20

FCAL Forward Calorimeter 11

GRL Good Runs List 15

HCAL Hadronic Calorimeter 8

HLT High Level Trigger 13

IBL Insertable B-Layer 9

ID Inner Detector 8

LB Luminosity-block 15

L1 Level-1 13

L1Topo Level-1 Topological 13

LAr Liquid Argon 11

LHC Large Hadron Collider 6

LHCb Large Hadron Collider beauty

LHCf Large Hadron Collider forward

MC Monte Carlo 17

MDT Monitored Drift Tube 12

MoEDAL Monopole & Exotics Detector At the LHC

MS Muon Spectrometer . . . 12

PS Parton Shower . . . 6

PSB Proton Synchrotron Booster . . . 6

PV Primary Vertex . . . 18

ROI Region of Interest . . . 13

RPC R-Parity Conserving . . . 12

RPC Resistive-Plate Chamber . . . 12

SCT SemiConductor Tracker . . . 9

SM Standard Model

SPS Super Proton Synchrotron . . . 6

SSV Shower Shape Variable . . . 20

TGC Thin-Gap Chamber . . . 12

TOTEM TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC

TRT Transition Radiation Tracker . . . 9

NSW New Small Wheel . . . 13

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