

Double B -hadron Jet Tagging and
Identification of Gluon to $b\bar{b}$ jets with the
ATLAS Detector

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**Double B -hadron Jet Tagging and Identification of
Gluon to $b\bar{b}$ jets with the ATLAS Detector**

Trabajo de Tesis para optar por el título de
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A Ricardo, a mi familia...

Abstract

El detector ATLAS, uno de los cuatro experimentos del acelerador LHC actualmente en construcción en el CERN, tiene como propósito principal el descubrimiento del bosón de Higgs, la partícula involucrada en el mecanismo de ruptura de la simetría electrodébil y el origen de la masa, así como la búsqueda de nueva física más allá Modelo Estándar hasta la escala de 1 TeV. En el colisionador chocarán haces de protones con una energía de centro de masa de 14 TeV y una frecuencia de interacción de 10^9 Hz.

This thesis describes a method that allows the identification of double B -hadron jets originating from gluon-splitting. The technique exploits the kinematic differences between the so called “merged” jets and single B -hadron jets using track-based jet shape and jet substructure variables combined in a multivariate likelihood analysis. The ability to reject b -jets from gluon splitting is important to reduce and to improve the estimation of the b -tag background in Standard Model analyses and in new physics searches involving b -jets in the final state. In the simulation, the algorithm rejects 95% (50%) of merged B -hadron jets while retaining 50% (90%) of the tagged b -jets, although the exact values depend on the jet p_T .

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Chapter 1

The ATLAS detector at the LHC

1.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is a proton-proton (pp) synchrotron located in the previous Large Electron Positron (LEP) collider tunnel at CERN Laboratory, just outside the city of Geneva (Switzerland), approximately 100 m underground. It is designed to collide bunches of up to $\sim 10^{11}$ protons every 25 ns at a center-of-mass energy of 14 TeV (seven times the 2 TeV reached by the Tevatron accelerator at Fermilab Laboratory, in Chicago).

The experiments analyzing the collisions produced by the LHC are distributed around the 27 km ring at the various interaction points. The ATLAS experiment is located at Point 1, which is closest to the main CERN site. Point 5 houses the other general purpose detector, CMS. ALICE and LHCb experiments are located at Point 2 and Point 8, respectively. The former is designed to investigate heavy ion collisions; the latter, to investigate rare decays of b-mesons. The layout of these four experiments along the LHC

ring is shown in Fig. 1.1.

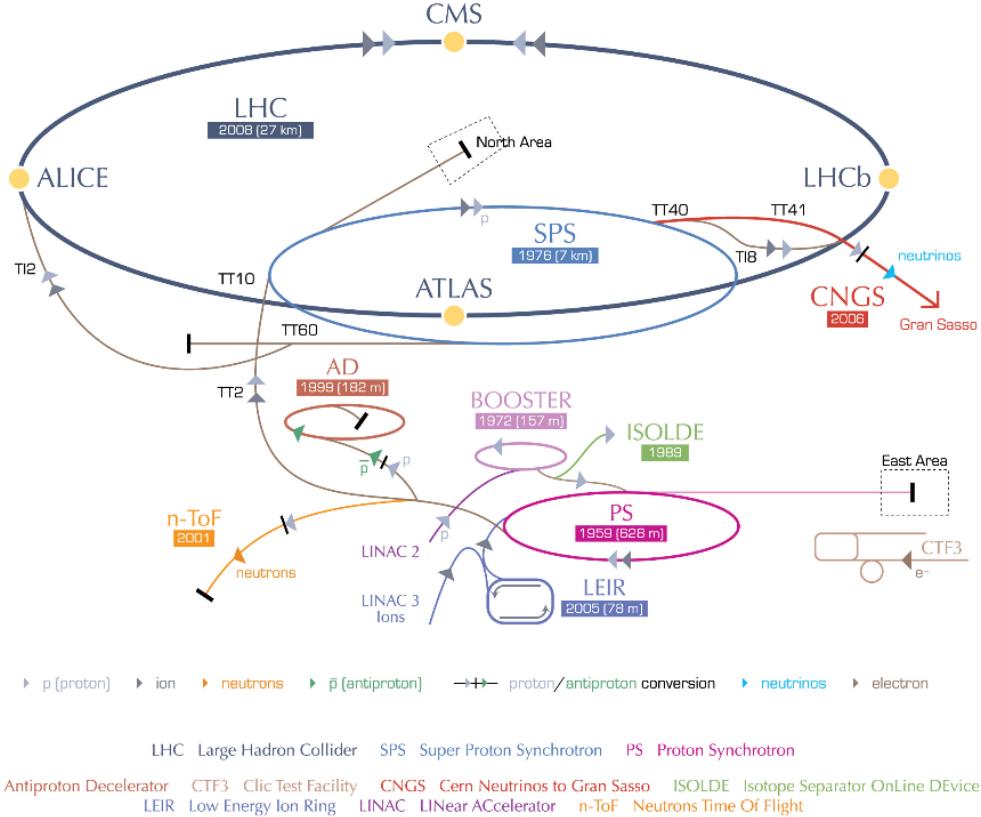


Figure 1.1: The CERN accelerator complex, showing the injection system, along with each components date of construction, and the placement of the four main experiments.

Proton beams are formed, before insertion into the main LHC ring, using a succession of smaller machines with increasingly higher energies, as shown in Fig. 1.1. The chain begins as protons are injected into the PS Booster (PSB) at an energy of 50 MeV from Linac2. The booster accelerates them to 1.4 GeV. The beam is then fed to the Proton Synchrotron (PS) where it is accelerated to 25 GeV. At desin strength, the bunch structure, known as a

bunch train, contains 72 bunches of protons upon entry to the Super Proton Synchrotron (SPS). The SPS accumulates up to four fills of 72 bunches from the PS and accelerates them to 450 GeV, with a bunch spacing of ~ 25 ns. They are finally transferred to the LHC (both in a clockwise and an anticlockwise direction) where they are accelerated for 20 minutes to their nominal energy of 7 TeV. Beams will circulate for many hours inside the LHC beam pipes under normal operating conditions.

The bunch structure is a direct consequence of a radio frequency (RF) acceleration scheme used to attain the desired high proton beam energy. In RF acceleration, particles travel through a series of time-varying electrical fields and they can only be accelerated when the RF field has the correct orientation when particles pass through an accelerating cavity, which happens at well specified moments during an RF cycle. The result of a sequence of RF accelerations is several bunches of protons. It is important to note that when we speak about “beams” we refer to many bunches of protons separated by some uniform distance. Increasing the number of bunches is one of the ways to increase luminosity in a machine (more about luminosity in subsection 1.1.1). At desinged beam intensitiy, when the bunches cross, there will be a maximum of about 20 collisions.

A larged magnetic field is needed to guide and maintain the beam particles in their circular orbit. The needed field is achieved using superconducting electromagnets built from NbTi coils that operate in a superconducting state, efficiently conducting electricity without resistance or loss of energy. The currents through the coils produce magnetic fiedls perpendicular to the direction of motion of the protons that deflect the protons into their orbits. The whole magnetic system comprises 1232 dipole magnets of 15 m length which are used to bend the beams, and 392 quadrupole magnets, each 57 m

long, to focus the beams. At a peak beam energy of 7 TeV, the dipoles need to produce an 8.33 T magnetic field, requiring a current of ~ 12 kA. In order to deliver the current densities and magnetic field required for 7 TeV proton beams, the magnets are kept at 1.9 K by circulating superfluid helium.

The first pp collisions produced by the LHC occurred on November 23 2009, at the SPS extraction energy of 450 GeV per beam. Very quickly after, on December 8, ATLAS and CMS detectors started recording data at energy of 2.36 TeV. By this time the LHC became the highest energy accelerator in the world. During this period, bunch intensities were limited by machine-protection considerations to 1.5×10^{10} protons.

In February 2010, the LHC was commissioned once more with 450 GeV beams, and a series of tests were performed to ensure that the magnet systems could operate safely at the currents necessary to control 3.5 TeV beams. This was followed by the very first collisions at 7 TeV center-of-mass energy on March 30. During the 2010 run the beam parameters were tuned (the beam widths squeezed and the number of protons per bunch and the number of bunches in each beam increased) in order to increase the beam intensity. In particular, as the intensity of the beams increased, the mean number of interactions per bunch crossing increased.

Finally, the data samples analysed in this thesis correspond to proton-proton collisions at $\sqrt{s} = 7$ TeV delivered by the LHC and recorded by ATLAS between May and November 2011, with the LHC running with 50 ns bunch spacing. Table ?? summarizes the basic beam parameters expected for design energy and luminosity and the beam parameters as of May 2011. The LHC performance steadily improved during 2011. The average number of interactions per bunch crossing throughout the data-taking period considered rapidly increased approximately from ~ 3 to 8 until (northern hemisphere)

summer 2011, with a global average for this period of ≈ 6 . Starting in August 2011 and lasting through the end of the proton run, this number ranged from approximately 5 to 17, with an average of about 12. This evolution is illustrated in Fig. 1.2, which shows the maximum mean number of collisions per beam crossing versus day in 2011.

Parameter	2011 runs	Design
Center-of-mass energy [TeV]	7	14
Instantaneous luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	3.65×10^{33} (year peak)	10^{34}
Bunches per beam	38 (May)	2808
Protons per bunch	0.8×10^{11} (May)	1.5×10^{11}
Mean interactions per crossing	6 to 12 (year average)	23

Table 1.1: Summary of beam conditions during the 2011 7 TeV runs and those foreseen at design energy and luminosity.

1.1.1 Luminosity and pile-up

The rate of events produced by the colliding beams depends on the luminosity of the collisions, which is a measure of the number of events per second per unit cross section, typically measured in units cm^2s^{-1} . The number of events of a particular process, then, is given by the product of the integrated luminosity, $\int dt L$, and the cross section of the process, σ_{event} . The integrated luminosities are typically quoted in units of inverse picobarns, $\text{pb}^{-1} = 10^{-36}\text{cm}^2$. In order to measure processes with very little cross sections a very high luminosity is required.

The delivered luminosity can be written as [2]:

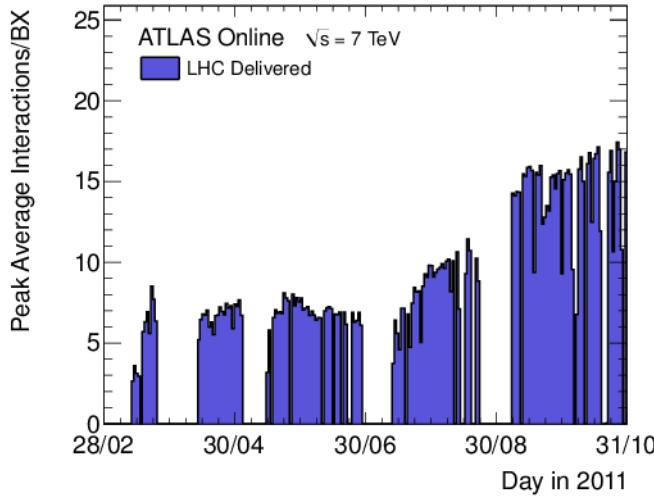


Figure 1.2: The maximum mean number of events per beam crossing versus day in 2011.

$$L = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \quad (1.1)$$

where n_b is the number of colliding bunch pairs, n_1 and n_2 are the bunch populations (protons per bunch) in beam 1 and beam 2 respectively (together forming the bunch charged product), f_r is the machine revolution frequency, and Σ_x and Σ_y are the width and the height of the proton beams.

The number of protons per bunch, the number of bunches per beam, and the revolution frequency are all set by the beam operators. The widths of the proton beams are measured in a process known as a Van der Meer (*vdm*) scan [3]. In a *vdm* scan, the beams are separated by steps of a known distance. The collision rate is measured as a function of this separation, and the width of a gaussian fit to the distributions yields the width of the beams in the direction of the separation.

The total integrated luminosities provided by the LHC and recorded by

ATLAS in 2011 are shown in Figure 1.3. These events form the dataset analyzed in this thesis. By means of the beam-separation or vM scans, as well as other techniques to measure the bunch charged product, the ATLAS Collaboration has determined that the uncertainty on its luminosity measurement is $\delta L = \pm 3.7\%$. For a complete description of the methods used and the systematic errors evaluated see reference [2].

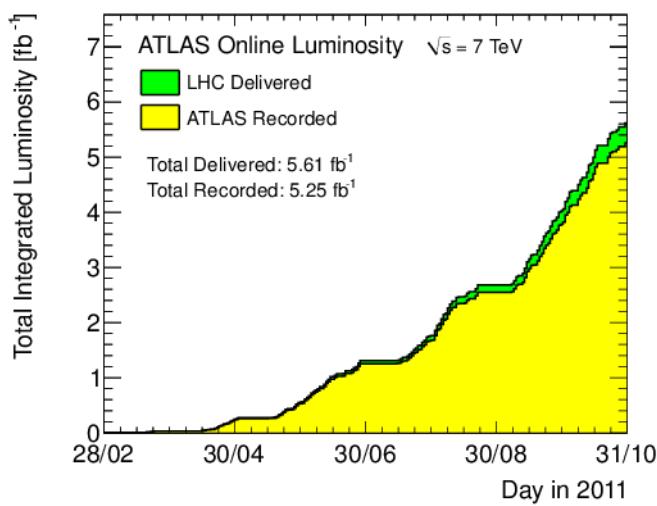


Figure 1.3: Total luminosity delivered by the LHC and recorded by ATLAS during the 2011 $\sqrt{s} = 7$ TeV proton-proton run

As anticipated, due to the cross-section for interaction and the number of protons per bunch, the possibility to observe multiple pp interactions per bunch crossing increases proportionally. This phenomenon, referred to as “pile-up”, can really occur in two distinct forms. The first form is the presence of multiple pp collisions (different from the interaction of interest) in the same bunch crossing, referred to as “in-time” pile-up. The second form of pile-up takes place due to electronic integration times within the detector. Certain detector components are actually sensitive to multiple bunch cross-

ings due to the long electronic signals generated in the response to energy depositions or charge collection. One or more pp collisions in a bunch-crossing different from that which produced the collision of interest can then affect the measurement. This form of pile-up is referred to as “out-of-time” pile-up and will become more and more important as the LHC bunch spacing gets closer to the nominal value, 25 ns.

The fraction of events with pile-up increased significantly since the data taking started. The experimental signature of this fact is obtain via the number of reconstructed primary vertices, or NPV. The effect of the event NPV is an important concern for the measurement of jet properties and will be discussed in the next chapters.

1.2 The ATLAS Detector

The ATLAS detector [4] is one of the two general purpose particle detectors built for probing pp collisions at the LHC. As it was described in the previous section, inside the LHC, bunches of up to 10^{11} protons will collide 40 million times per second to provide 14 TeV proton-proton collisions at a nominal luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. These high interaction rates and energies, as well as the requirements for high precision physics measurements set the standars for the design of the detector. At even 7 TeV center-of-mass energy, the LHC interactions result in high particle multiplicity, requiring fine detector granularity, and particle production at forward rapidity, requiring large detector angular coverage.

To achieve these performance goals, a design consisting of multiple detector sub-systems with cylindrical symmetry around the incoming beams is used as shown in Fig. 1.4. Closest to the interaction point the inner tracking

detector is placed, providing charged particle reconstruction. The magnet configuration comprises a thin superconducting solenoid surrounding the inner detector cavity, and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. This fundamental choice has driven the design and size (44 m in length and 25 m in height) of the rest of the detector. Outside the solenoid, a calorimeter system performs electron, photon, tau, and jet energy measurements. Finally, the calorimeter is surrounded by the muon spectrometer where an array of muon drift chambers perform muon identification and momentum measurements.

The ATLAS detector coordinate system is used to describe the position of particles as they traverse these subdetectors. It is a right-handed coordinate system, with z pointing along the beam direction, positive x pointing toward the center of the LHC ring, and positive y pointing up. The $x-y$ plane is referred to as the transverse plane, and the z direction as the longitudinal direction. The azimuthal angle ϕ is measured as usual around the beam axis, and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = \ln \tan(\frac{\theta}{2})$, regions of low η are referred to as “central”, and regions of high η are referred to as “forward”. The transverse momentum p_T is defined in the $x-y$ plane unless stated otherwise. The distance ΔR in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

To meet the extremely high demands that the LHC luminosity places on the speed with which ATLAS must record data, a dedicated trigger and data acquisition (TDAQ) system is used. The interaction rate at the design luminosity is approximately 1 GHz, while the event data recording, based on technology and resource limitations, is limited to about ~ 200 Hz. This requires a high rejection of minimum-bias processes while maintaining max-

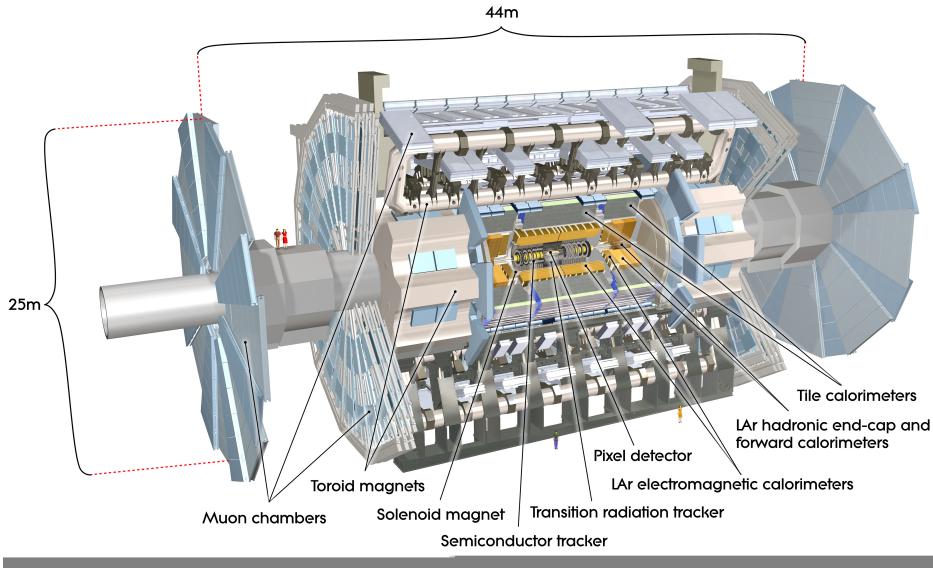


Figure 1.4: El detector de ATLAS

imum efficiency for the new physics. The Level-1 (L1) trigger system uses a subset of the total detector information to make a decision on whether or not to continue processing an event, reducing the data rate to approximately 75 kHz (limited by the bandwidth of the readout system, which is upgradeable to 100 kHz). The subsequent two levels, collectively known as the high-level trigger (HLT), are the Level-2 (L2) trigger and the event filter. They provide the reduction to a final data-taking rate of approximately 200 Hz.

1.2.1 Inner tracking system

The inner tracking system or inner detector (ID) is composed of three sub-detectors: the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT). The goal of these three is to provide charged

particle trajectory reconstruction and momentum measurements with an overall acceptance in pseudorapidity of $|\eta| < 2.5$ and full ϕ coverage.

The sensors which built this system register signals, referred to as “hits”, in response to the passage of charged particles. The ID is immersed in a 2 T magnetic field, generated by the central solenoid. The positions of the registered hits are combined to form tracks, with the radius of curvature of the tracks (caused by the presence of the magnetic field) providing a measurement of the particles transverse momentum. The track reconstruction efficiency ranges from 78% at $p_T^{track} = 500$ MeV to more than 85% above 10 GeV, averaged across the full η coverage [5]. The transverse momentum resolution of $\sigma_{p_T}/p_T = 0.05$ [6] (upper bound) and a transverse impact parameter resolution of $\sim 20 \mu m$ for high momentum resolution particles in the central η region[7].

The pixel detector, SCT, and TRT sensors are arranged on concentric cylinders around the beam axis, known as barrel layers, and on disks perpendicular to the beam at either end of the barrel, known as end-caps. A more complete description of these systems is given below. The overall layout of the inner detector is shown in Fig. 1.5.

The Pixel detector

The pixel detector consists of three concentric barrel layers. The innermost one, the so called “b-layer” due to its role in identifying b -quarks initiated jets, is located at 5 cm from the interaction region. Three additional disks are located at each end-cap, producing typically three pixel position measurements per charged particle track. Each layer or disk is instrumented with modules that form the basic unit of data acquisition, each with 47232 pixels. All pixel sensors are identical and have a minimum pixel size in r

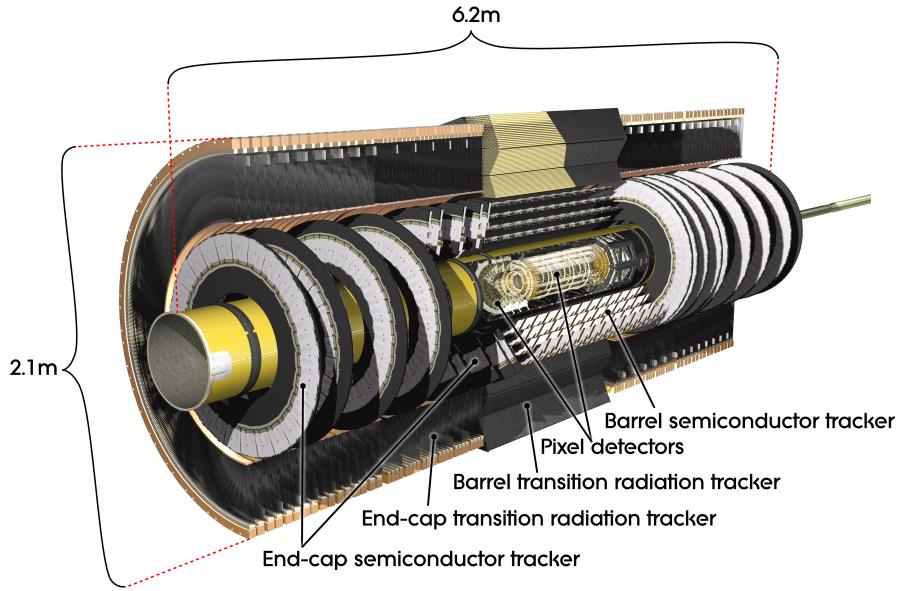


Figure 1.5: Layout of the ATLAS inner detector.

- $\phi \times z$ of $50 \times 400 \mu\text{m}^2$. The intrinsic accuracies in the barrel are $10 \mu\text{m}$ in $r - \phi$ and $115 \mu\text{m}$ along z , or along r in the end-caps. The pixel detector has approximately 80.4 million readout channels, an order of magnitude more readout channels than the rest of ATLAS combined, and it extends to a total length of $z \sim \pm 650 \text{ mm}$ and radius of $r \sim 150 \text{ mm}$, providing good reconstruction efficiency for tracks up to $|\eta| < 2.5$.

The SCT

The SCT consists of four barrel layers and nine end-cap layers surrounding the pixel detector, resulting in at least four hits along every charged particle track. The SCT barrel reaches to $z \sim \pm 750 \text{ mm}$ and $r \sim 515 \text{ mm}$, while the end-cap covers out to $z \sim \pm 2720 \text{ mm}$ and $r = 560 \text{ mm}$. There are 15,912 SCT module sensors, each 12.8 cm long and approximately $285 \mu\text{m}$ thick.

In the barrel region, these modules use small-angle (40 mrad) stereo strips to measure both coordinates, with one set of strips in each layer parallel to the beam direction, measuring the ϕ coordinate directly . In the end-cap region, the detectors have a set of strips running radially and a set of stereo strips at an angle of 40 mrad. The mean pitch of the strips is 80 μm . The intrinsic accuracies per module in the barrel are 17 μm in $r - \phi$ and 580 μm in z (or r in the end-caps). The total number of readout channels in the SCT is approximately 6.3 million. A hit is registered only if the pulse height in a channel exceeds a preset threshold (~ 1 fC). The charged measured in the strip is then recorded into a memory buffer that is only read out and used for tracking if a trigger is received signaling that the event should be considered in more detail.

The TRT

The TRT surrounds the silicon detectors and is comprised of up to 76 layers of longitudinal straw tubes in the barrel, extending to $z \sim \pm 710$ mm and $r \sim 1060$ mm, and 160 radial straw planes in each end-cap cylinders, reaching $z \sim \pm 2710$ mm and $r \sim 1000$ mm.

The TRT sensors are thin drift tubes consisting of cathode metal straws filled with an ionizing gas mixture of xenon, oxygen, and CO₂, with an anode wire running down the center of the straw. The passage of a charged particle through the gas produces positive ions and free electrons, which travel to the cathode and anode, respectively, under the influence of an applied voltage of 1600 V. Comparing the time that the signals are received at the cathode and the anode gives a drift time measurement that can be used to calculate the impact parameter of the particle. This method gives no information on the position along the length of the straw.

To give the best resolution of particle trajectories as they bend in the solenoidal field, the straws lie along the beam direction in the barrel and radially in the end-caps. The straw diameter of 4 mm causes a maximum drift time of approximately 48 ns and an intrinsic accuracy of 130 m along the radius of the straw.

In addition to directly detecting charged particles produced by the collision, the TRT also measures the transition radiation induced by the passage of these particles through polypropylene sheets placed between the drift tube straws. Transition radiation refers to the photons emitted by charged particles as they pass from one material into another with a different dielectric constant. These photons yield a much larger signal amplitude than the charged particles, so separate thresholds in the electronics can be used to distinguish the two.

One of the most important tasks of the inner detector is to provide accurate collision vertex identification, exploiting the excellent position resolution and tracking efficiency. Vertices are reconstructed by matching inner detector tracks with $p_T > 150$ MeV back to a common origin.

1.2.2 The Calorimeter System

The purpose of the ATLAS calorimeter system is to measure the energy of electrons, photons, taus and jets, within the pseudorapidity region of $|\eta| < 4.9$ and with full ϕ symmetry and coverage around the beam axis. It also provides fast position and energy measurements to serve as trigger signals for these objects as well as the missing transverse energy.

The calorimeter detector consist of electromagnetic (EM) calorimeter and hadronic calorimeter components. The EM calorimter provides fine granularity measurements of electrons and photons. Each calorimeter is segmented

both transverse to the particle direction, to give position information, and along the particle direction, to chart the development of the particle shower. This permits detailed mapping of EM and hadronic showers in the calorimeter, allowing for studies of the internal structure of hadronic jets and partially giving rise to the high resolution measurements of their energy.

The EM and hadronic calorimeters are sampling calorimeters meaning that they utilize alternating layers of absorber material, composed of heavy atoms that interact with energetic particles and cause them to lose energy, and an active material, that produce a signal in response to the deposited energy.

The calorimeters closest to the beam-line are housed in three cryostats, one barrel and two end-caps. The barrel cryostat contains the electromagnetic barrel calorimeter, and the two end-cap cryostats each contain an electromagnetic end-cap calorimeter (EMEC), a hadronic end-cap calorimeter (HEC), located behind the EMEC, and a forward calorimeter (FCal) to cover the region closest to the beam. These calorimeters use liquid argon as the active detector medium and need to be maintained at a constant temperature of $\sim 88\text{K}$. Liquid argon (LAr) has been chosen for its intrinsic linear behaviour (production of ionization charge as a function of incident charge), its stability of response over time and its intrinsic radiation-hardness.

An illustration of all these components can be found in Fig. 1.6. Further specifications are given in the next sections.

Liquid argon EM calorimeter

The EM calorimeter uses lead as the absorber and liquid Argon as the active material. A photon traversing the absorber will interact with the heavy nucleus via Compton scattering or the photo-electric effect, producing low-

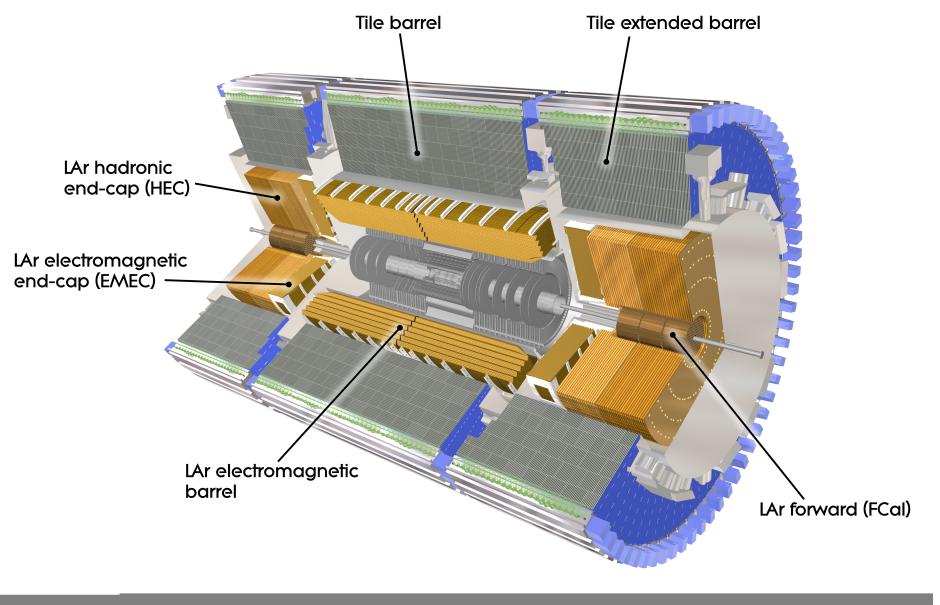


Figure 1.6: Layout of the ATLAS electromagnetic and hadronic calorimeter systems. The total length is ~ 12 m, extending to a maximum radius of 4.25 m.

energy electrons, or pair production, producing electron/positron pairs. An electron or positron, in turn, can produce bremsstrahlung photons as it is deflected by the nuclei or produce more charged particles via ionization. Thus each incident photon, electron, or positron produces a shower of photons, electrons, and positrons that lose their energy through successive interactions in the absorber. The produced particles ionize the liquid argon, and the charge is collected by electrodes located in the liquid argon gap. These electrodes consist of three layers of copper sheets, the outer two kept at high-voltage potential and the inner one used to readout the signal.

To provide full coverage in ϕ without any cracks, an accordion-shaped absorber and electrode geometry is used, shown in Fig. 1.7. This design was chosen to ensure high azimuthal uniformity, a regular liquid argon ionization gap, and a constant sampling fraction within a given detector region. The figure highlights how this geometry is divided among rectangular cells in $\eta \times \phi$ space, the individual readout elements of varying size, finely segmented both laterally and longitudinally. Such fine segmentation $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in the second layer of the EM barrel, for example permits a detailed mapping of the electromagnetic and hadronic showers.

The position resolution of the EM is driven by the readout geometry (rectangular cells). There are three layers of cells, segmented along the particle’s direction of motion. The ϕ segmentation comes from grouping the accordion-shaped electrodes together into a common read out channel.

In the region $0 < |\eta| < 1.8$ the electromagnetic calorimeters are complemented by a “presampler” detector, an instrumented argon layer, which provides a measurement of the energy lost in the solenoid and the outer wall of the barrel cryostat.

The signal readout chain for the LAr calorimeter (indeed for all calorime-

ter systems) is divided into a fast analog readout for the trigger system and a slower digital readout used for more redefined trigger decisions and the offline reconstruction. However, regardless of the readout path, the signal is initiated within the active LAr medium. Shaping electronics induce a bipolar pulse shape in the ionization signal. This shape is characterized by having both a positive and a negative component, which renders the integral of the signal exactly equal to zero.

The performance of the shaping electronics is critical for a correct energy calibration of the detector since the energy is primarily determined from the peak height of the pulse. In each calorimeter region, the overall pulse shape and duration are optimized to approximately cancel a constant injection of energy into the detector. The motivation for this approach is to effectively redefine the baseline of the energy measurement. In the high luminosity environment of the LHC, this reduces the sensitivity to the background from multiple pp interactions on average.

Finally, the EMEC uses the same accordion geometry as the EMB, whereas the granularity is typically slightly larger than in the barrel.

The hadronic calorimeter

Outside the EM calorimeter lies the system of hadronic calorimeters. The barrel portion, known as the Tile calorimeter, uses iron absorber slabs interspersed with scintillating tiles. The Tile calorimeter is most notable for its depth of 7.4 radiation lengths (λ^1). The hadronic end-cap and the forward calorimeter, which need to absorb the more energetic particles that are pro-

¹To quantify the amount of material needed to capture a particle's energy, the unit of an interaction length, which is the distance over which a high energy charged particle loses $1 - \frac{1}{e} \sim 63\%$

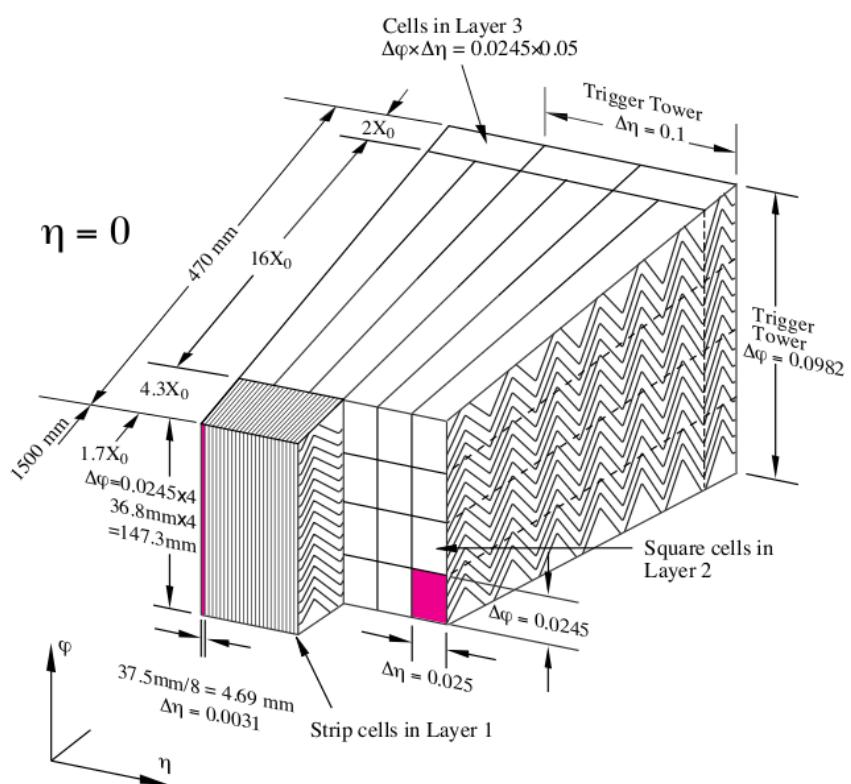


Figure 1.7: Cross section of the LAr barrel calorimeter where the different layers are visible. The granularity in η and ϕ of the cells of each of the three layers is also shown.

duced at large $|\eta|$, are made of copper and tungsten absorbers, respectively, with liquid argon as the active material.

The tile calorimeter is composed of 3 mm thick scintillating tiles, arranged to lie parallel to the incoming particle direction, interleaved with 14 mm thick iron plates. It is divided into the barrel calorimeter, covering $|\eta| < 1.0$, and two extended barrel calorimeters, covering $0.8 < |\eta| < 1.7$. Each tile is read out by two wavelength-shifting fibers, which convert the scintillator signal to visible light. The readout fibers of several tiles are grouped to a single photomultiplier tube forming cells in $\eta \times \phi$ space. As in the EM calorimeter, these cells are segmented into three layers, the first two of size $\Delta\eta = 0.1$ and $\Delta\phi = 0.1$ and the last of size $\Delta\eta = 0.2$ and $\Delta\phi = 0.1$. Towers to provide information to the trigger system are formed from 0.1×0.1 grouping of all three layers.

1.2.3 The Muon System

El sistema de muones sirve a un doble propósito: funciona como sistema de disparo (o *trigger*) para la selección de eventos con muones de alta energía, y como espectrómetro de muones de alta precisión. En este sentido, este detector llevará a cabo la identificación de los muones producidos en las colisiones p - p , determinando sus trayectorias y momentos. El sistema consiste en un conjunto de toroides (llamamos así, por su forma, a los tres conjuntos de bobinas que proveen el campo magnético toroidal) y cámaras de tubos de deriva que se encuentran rodeando al calorímetro. En la parte del baril del detector, las cámaras están situadas en el interior del toroide lo que permite la medición del momento de las partículas a partir de la desviación de sus trayectorias en el campo magnético. En las tapas, donde la presencia del crióstato impide posicionar las cámaras dentro del campo magnético, el

momento es medido a partir de la diferencia entre los ángulos de entrada y salida del imán. En el plano trasversal, tanto en la región del barril como en las tapas laterales, el sistema de cámaras estará dividido en 16 sectores, siguiendo la simetría determinada por las 8 bobinas del barril central del sistema magnético. Las cámaras cubren el espacio entre las bobinas, y todo el rango acimutal en la región que las rodea. Los sectores se numeran comenzando a partir de $\phi = 0$, en el sentido contrario de las agujas del reloj, teniendo en la dirección vertical a los sectores 6 (en la parte superior del detector) y 13 (sector inferior).

Los cámaras de tubos de deriva (MDTs) son cámaras proporcionales hechas de tubos de aluminio de 30 mm de diámetro y longitudes variables de 70 a 630 cm, con un hilo central de $50\mu\text{m}$ de diámetro, de W-Re. En la región del barril dichas cámaras están distribuidas en 3 capas cilíndricas concéntricas (estaciones) alrededor del haz, de 5; 7,5 y 10 metros de radio. Los tubos están dispuestos de manera transversal al eje z de manera de medir la coordenada en el plano de desviación de la trayectoria de la partícula (plano Rz). Estas cámaras miden el tiempo de deriva de la ionización producida por el paso del muón, teniendo una resolución de $80\mu\text{m}$.

Cada cámara MDT está cubierta por una o dos cámaras de placas resistentivas (RPCs). Cada una de ellas encierra un volumen de gas entre planchas resistentivas de baquelita, dotada una de ellas con tiras de electrodos. Dado que los tubos de deriva poseen un diámetro relativamente grande que resulta en un tiempo de deriva máximo de 480ns, mucho mayor que los 25 ns entre cruce de *bunches*, se requieren cámaras especiales de disparo para la selección de eventos. La función de trigger en el barril es provista por tres capas de RPCs, situadas, dos de ellas, a ambos lados de la segunda estación de MDTs y la restante, en la cara interior de la estación más externa. En

las tapas, esta función es cumplida por tres estaciones de TGCs (*Thing Gap Chambers*). Estas cámaras son similares en diseño a cámaras proporcionales multihilo, con la diferencia de que poseen una distancia cátodo-cátodo menor que la pendiente del ánodo (hilo). Las cámaras de disparo proveen una estimación de las coordenadas ϕ y η del punto de impacto de la traza, mientras que las cámaras MDTs darán (con mayor precisión) la coordenada η .

En la región de bajo ángulo, donde la densidad de trazas es mayor, se utilizan cámaras de tiras de cátodos (CSCs) de granularidad más fina comparadas con las MDTs, para la detección de trayectorias. Estas cámaras son cámaras proporcionales, con un espacio entre hilo de 2,5 mm. Cada una de ellas proporciona medida de dos coordenadas y puede operar en condiciones de alto campo magnético.

En la figura 1.8 se puede ver un esquema del espectrómetro de muones, donde se indica la posición de las diferentes cámaras descriptas.

El sistema de imanes superconductores de ATLAS consiste en un solenoide central que provee el campo magnético necesario al detector interno, rodeado por un arreglo de bobinas o bucles, con forma de pista de carrera, que generan un campo magnético toroidal para el espectrómetro de muones. Todo el sistema es enfriado de manera indirecta mediante el flujo de helio líquido a 4,5 K.

El solenoide es un electroimán superconductor de 5,3 m de largo, situado en el interior del calorímetro electromagnético. Comparte el crióstato con el calorímetro de argón líquido, evitando la presencia de dos paredes criostáticas y reduciendo así la cantidad de material introducido. La longitud del solenoide es considerablemente más pequeña que la del barril del detector de trazas. Este es el resultado de un compromiso: un bobinado corto reduce la cantidad de material introducido mientras que uno largo pro-

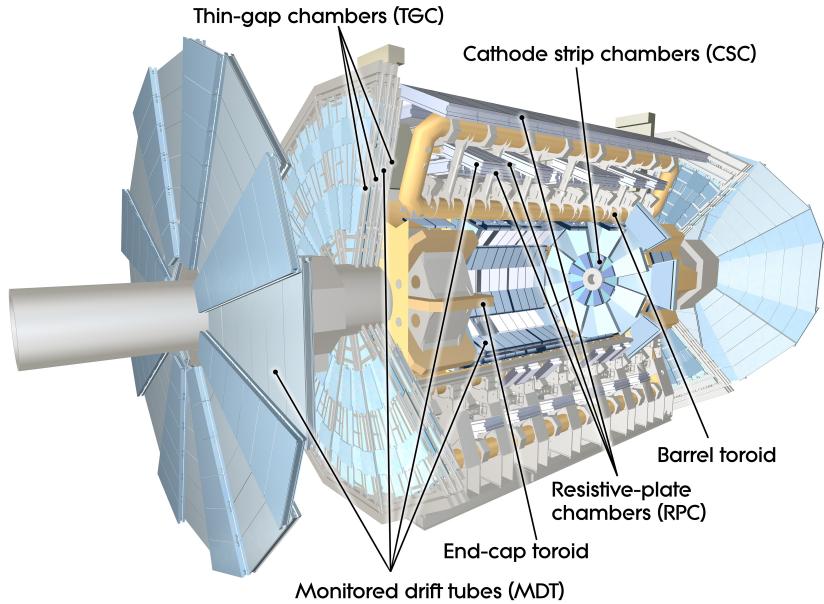


Figure 1.8: Muon Chamber

porciona un campo magnético más uniforme en dicho detector. El campo magnético a lo largo del eje z es de 2 T en el punto de interacción.

El arreglo de bobinas está dividido en un barril central y dos regiones laterales, al igual que los detectores. El barril central está constituido por 8 bobinas de 5 m de ancho por 25 metros de largo aproximadamente, dispuestas simétricamente alrededor del haz de manera radial. Las bobinas del barril se encuentran en crióstatos separados, mientras que las 8 bobinas en cada una de las tapas o toroides laterales están ubicadas en un crióstato común.

Con un campo magnético toroidal las partículas atravesarán todo el rango de pseudorapidez casi perpendicularmente al haz. El número pequeño de bobinas que generan el campo toroidal resulta en una intensidad de campo que varía fuertemente con la coordenada ϕ . En el barril el campo magnético es de 2 T, mientras que en las tapas es de 4 T en las zonas de mayor inten-

sidad.

1.2.4 Trigger and Data Adquisition

En este capítulo se analiza la estructura del trigger de ATLAS, y el sistema de adquisición y flujo de los datos. Se presenta, asimismo, una breve descripción de los algoritmos usados en la reconstrucción de trayectorias para la selección de eventos en el detector interno.

Arquitectura general

El sistema de Trigger y Adquisición de Datos[?] de ATLAS está basado en tres niveles de selección *online*: Nivel 1, Nivel 2 y Filtro de Eventos. Cada nivel es más lento pero más preciso que el anterior. Trabajando con una frecuencia de interacción de 10^9 Hz y luminosidades del orden de $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, este sistema será el encargado de reducir la frecuencia de eventos inicial de 40 MHz a 200Hz, que es la velocidad con la que pueden almacenarse.

En la figura 1.9 se muestra un vista simplificada de los principales componentes y funciones.

El mecanismo que lleva a cabo el movimiento de la información (Data Flow System), es el responsable de recibir los datos de los detectores, pasando parte de ellos al sistema de trigger y enviando luego, los eventos seleccionados al lugar de almacenamiento. Siguiendo el esquema de la figura, la comunicación entre los *drivers* de lectura de cada detector (RODs) y el sistema de adquisición de datos, está dada por los *buffers* de almacenamiento transitorio (ROBs). La información de los eventos aceptados por el Nivel 1 son transportados de los primeros al sistema de lectura (ROS), que consta de numerosos ROBs, guardando los datos a la espera de la decisión del trigger. La información requerida por el segundo nivel es provista por estos últimos.

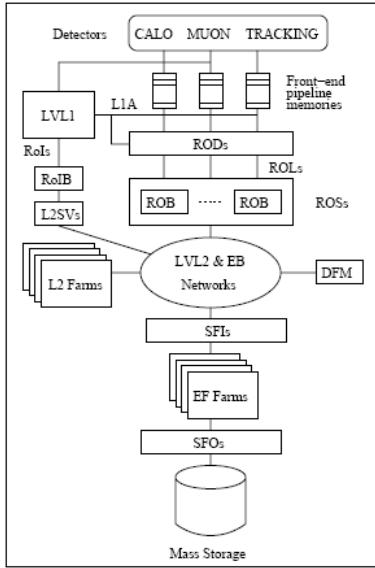


Figure 1.9: Principales componentes del sistema de trigger y adquisición de datos de ATLAS.

Los eventos aceptados son reconstruidos (a partir de fragmentos contenidos en diferentes ROBs) y pasados al siguiente nivel.

El Nivel 2 y el Filtro de Eventos componen el *High-level Trigger* (HLT) de ATLAS. El Nivel 2 trabaja a la frecuencia de aceptación del Nivel 1, utilizando una secuencia de rápidos algoritmos de selección que operan típicamente sobre una fracción de los datos del evento, contenida en regiones del detector previamente seleccionadas por ese nivel (ver el mecanismo de la región de interés en la siguiente sección). Si la decisión del Nivel 2 es rechazar el evento, los datos del mismo son eliminados de los buffers correspondientes. Si el evento es aceptado, se reconstruye en el EB (Event Builder) y es pasado al Filtro de Eventos. Este nivel ejecutará algoritmos de reconstrucción más sofisticados, adaptados de aquellos para el análisis *offline*, utilizando información detallada de los detectores para efectuar el proceso de selección final,

que determinará cuáles son los eventos que serán guardados para posteriores estudios.

En las siguientes secciones se presenta una descripción más detallada de los niveles de trigger.

El Nivel 1

El primer nivel de trigger de ATLAS es implementado mediante hardware. Éste realiza una decisión inicial a partir de la información provista por los calorímetros y del detector de muones, basando su estrategia en la combinación de objetos en coincidencia.

En el sistema de muones, los candidatos de alto momento transverso son identificados en las cámaras especiales de trigger: RPCs en el barril y TGCs en las tapas. En el caso del calorímetro, se definen una serie de conjuntos de umbrales de p_T para cada objeto (electrones, fotones, jets, etc.), seleccionando aquellos que pasen los criterios de selección correspondientes al evento físico de interés.

Puesto que la decisión de aceptar un evento no puede ser realizada en los 25 ns que median entre dos cruces de *bunches*, los subdetectores almacenan localmente la información del mismo en *pipelined buffers* hasta que el Nivel 1 efectúa la selección. Luego, los datos son enviados a los RODs específicos de cada detector para luego dirigirse a los ROBs, donde son almacenados hasta que la decisión del Nivel 2 sea alcanzada. Cuando un evento es aceptado, el Nivel 1 comunica la decisión al mecanismo que se encargará de construir una Región de Interés (RoI). Este mecanismo es una importante pieza sobre la que descansa la estrategia del sistema de trigger; a través del mismo, el Nivel 2 hará uso de la información del evento en regiones localizadas del detector, de manera que los algoritmos de reconstrucción en ese nivel sólo transfieran

los ROBs necesarios para arribar a una rápida decisión. La RoI contendrá la información de la posición (η y ϕ) y el momento de los objetos candidatos.

Este nivel está diseñado para llevar a cabo su decisión en un tiempo menor a $2.5 \mu\text{s}$, medidos desde la colisión p - p , hasta que la información del evento está disponible en la electrónica de salida de los detectores. En este proceso la frecuencia de eventos será reducida a 75KHz (límite fijado por la electrónica).

1.2.5 El HLT

El High-level Trigger de ATLAS abarca la segunda y tercera etapa de la selección de eventos. Comprende el Nivel 2 y el Filtro de Eventos, y contiene además, el Software de Selección (ESS). Este último comparte la estructura usada por el Offline para los códigos de selección, facilitando el análisis *offline* de los datos, y el desarrollo de algoritmos en el HLT.

El punto de entrada del trigger es el resultado del Nivel 1. Éste provee información acerca de la región de interés, fundamental para el rápido funcionamiento de los algoritmos del Nivel 2. Así, los datos del Nivel 1 guían la selección del Nivel 2; y ésta a su vez guiará la del Filtro de eventos, como se ilustra en la figura 1.10.

El Nivel 2

La tarea específica del Nivel 2 es reducir la frecuencia de eventos de ~ 100 kHz a alrededor de 2 kHz, combinando la información de todos los detectores para su decisión global. A diferencia del Nivel 1, esta segunda etapa de selección realiza operaciones no sincronizadas sobre los eventos, con un tiempo de decisión de 10 ms.

El Nivel 2 utiliza las regiones de interés provistas por el Nivel 1. Cada

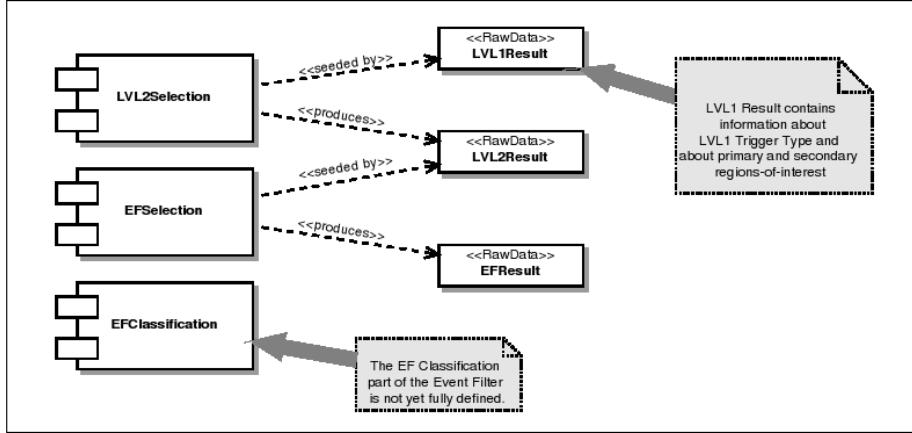


Figure 1.10: Cadena de selección del *High-level Trigger* de ATLAS. Cada nivel es guiado por el resultado del paso anterior.

región es examinada en el subdetector de origen (calorímetro o sistema de muones) para su confirmación; para luego buscar información de otros subdetectores. En el caso del trigger de muones, el poder de rechazo del Nivel 2 proviene de ajustar los umbrales de p_T , respecto de los utilizados en el primer nivel, a partir de la información de las cámaras de precisión del sistema de muones (MDTs) y la correspondiente al detector interno. Los procesadores del Nivel 2 son los encargados de ejecutar luego el software de selección de eventos, utilizando la información almacenada en los *buffers*. Usando las RoIs del Nivel 1, el Nivel 2 accederá de manera selectiva a los datos en los ROBs, moviendo sólo la información requerida para efectuar la decisión. Típicamente, sólo una pequeña fracción del detector, correspondiente a las regiones centradas en los objetos indicados por el Nivel 1, serán necesitados por el segundo nivel.

Hasta que un evento es aceptado o rechazado (en ~ 10 ms), los datos son retenidos en los ROBs. En caso de aceptación, los fragmentos del evento

almacenados en distintos buffers serán requeridos por el sistema de control del Nivel 2 (L2SVs) para ser enviados al constructor de eventos (EB). El evento ensamblado es guardado en una única dirección de memoria para ser utilizado por el Filtro de Eventos. El tamaño promedio de un evento será del orden de 1,5 MB.

El Filtro de Eventos

Luego del Nivel 2, la última etapa de selección *online* es realizada por el Filtro de Eventos (EF). El EF emplea algoritmos y métodos similares a los implementados en el análisis *offline*, adaptados para su corrida en el tiempo real del experimento; su poder de rechazo radica en el uso de algoritmos y criterios de selección más complejos, que por límites en el tiempo de procesamiento no pueden ser utilizados en el Nivel 2.

El EF utilizará información actualizada de la calibración y alineamiento del detector y un completo mapa del campo magnético; llevando a cabo con ello la selección final del evento físico que será guardado para su estudio en el Offline. La frecuencia de aceptación del nivel anterior será reducida en un orden de magnitud, almacenando a una tasa de \sim 100 MB/s.

El software de selección

La tarea del software de selección (ESS) es la selección y clasificación de los eventos. Candidatos tales como electrones, jets, muones, etc., representados por objetos abstractos, son reconstruidos utilizando un particular conjunto de algoritmos. Un evento es seleccionado si el objeto reconstruido satisface al menos una de las signaturas establecidas en el menú del sistema de disparo. En el Nivel 2 y el Filtro de Eventos (EF), los eventos serán rechazados si no pasan los específicos criterios de selección, diseñados para la reducción de la

frecuencia de eventos, al límite dado por la velocidad a la que éstos pueden ser almacenados.

El ESS se compone de una infraestructura y un conjunto de programas de selección para las dos etapas del HLT. Los algoritmos de reconstrucción para el trigger están basados en aquellos utilizados para la reconstrucción *offline*, pero correrán *online* en el entorno de software provisto por los procesadores del Nivel 2 y el EF.

De manera de facilitar el desarrollo de los algoritmos del HLT y simplificar los estudios del Offline; el ESS ha sido diseñado de manera de poder ser ejecutado directamente en el entorno provisto por la estructura de software de análisis offline del experimento, ATHENA[?]. La estructura dada por este paquete de software es lo suficientemente flexible como para abarcar una variedad de procesos, incluyendo no sólo algoritmos de trigger sino también tareas de calibración y monitoreo. Se ha destinado un apéndice (A) para su descripción.

En el Offline, la tarea del ESS es la de emular la cadena completa de selección *online*. Para su ejecución el sistema se sirve de cuatro sub-paquetes: el direccionamiento o *Steering*, los algoritmos del HLT, y los paquetes de software para la clasificación y movimiento de los datos, EDM (*Event Data Model*) y el DM (*Data Manager*). Los últimos toman los datos del evento en el formato que poseen a la salida de los sistemas de lectura (*Raw data* en formato *byte stream*), y los convierten en objetos que puedan ser usados por los algoritmos en la cadena de selección (*Raw Data Objects*).

La tarea de los algoritmos del HLT es la de analizar los datos del evento, reconstruyendo partes del mismo, luego de la selección del Nivel 1. El paquete se compone de dos subconjuntos principales:

- Programas de preparación de datos. Son los algoritmos ejecutados por

los sistemas EDM y DM para la conversión del formato de los datos del evento.

- Algoritmos FEX o de *Feature Extraction*. Comprende los programas de reconstrucción y los llamados algoritmos de “hipótesis”. Estos últimos (a los primeros nos referiremos en la siguiente sección) son aquellos programas que se encargan de eliminar, una vez realizada la reconstrucción, aquellos candidatos que no cumplen con las características o atributos asignados al evento físico en consideración (hipótesis), aplicando específicos criterios de selección. La presencia de los algoritmos de hipótesis es fundamental en la secuencia del HLT ya que evita la ejecución innecesaria de algoritmos al descartar eventos en las primeras etapas de la cadena.

Por último, el subpaquete de *Steering* es aquel que organiza el procesamiento de los datos del evento en el Nivel 2 y el Filtro de eventos; controlando el orden en el que los algoritmos de reconstrucción e hipótesis son ejecutados. El Steering define la secuencia del HLT, y manipula los resultados en cada paso de selección de manera que la decisión del trigger sea alcanzada.

1.2.6 Data quality

1.2.7 Simulation of particle interactions in the ATLAS Detector

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